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# SOIL SCIENCE

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## James Kenneth Wilson

### 1881-1948

James Kenneth Wilson, professor of soil technology at Cornell University and a consulting editor of *SOIL SCIENCE*, died July 28 in the Waterbury (Connecticut) Hospital

Professor Wilson was well known in this and other countries for his research in microbiology. He published an unusually large number of valuable papers covering a wide range of subjects. Moreover, he had to his credit many graduate students who keenly regret his passing. As a teacher and director of research, he was enthusiastic, helpful, and unusually patient. His perseverance and industry were phenomenal. Few men possessed a more winning and likable personality—cheerful, friendly, and cooperative.

During his 36 years at Cornell University, Dr. Wilson explored many phases of microbiology, but three lines of research claimed his major attention. These, in order of the intensity of their investigation, were first, the nodule organisms of legumes and their cross-inoculation peculiarities and capacities, second, methods of preservation of grass and legume silages especially in respect to keeping properties and quality, and third, the presence of nitrates and nitrites in the plant foods of humans and domestic animals and their nutritional significance.

Wilson was born August 5, 1881, in Maryville, Missouri, and passed his boyhood days on a ranch in Oklahoma. Here he received his early education, and here he acquired a love for and a curiosity in respect to plant and animal life. Conditions were hard in those days on the plains of Oklahoma, but, in his quest for a higher education, he was able to attend the Oklahoma Agricultural and Mechanical College, from which he received the degree of bachelor of science in 1906. His scholarship and promise were such that he immediately was offered a position at the New York State Agricultural Experiment Station at Geneva. Here, as assistant bacteriologist, young Wilson did his first real research. During six productive years at this institution, he finally decided in what particular field his life work was to lie.

Realizing the need for further scientific training, Wilson came to Cornell University in 1912 as an assistant in plant physiology and as a candidate for the Ph.D. degree. This degree was granted him in 1914. Because of his excellent record, he was offered forthwith and accepted an assistant professorship in soil technology to pursue research and teaching in the field of soil microbiology. In 1919, Dr. Wilson was raised to a full professorship, a position he occupied ably until his death.

Professor Wilson was a member of Sigma Xi, the American Association for the Advancement of Science, the American Society of Agronomy, and the Society of American Bacteriologists.

Although a man of strong personality and intense enthusiasm, Professor

Wilson never forced his ideas upon others, nor did he advertise his achievements. In fact, he was most modest and unassuming. His heart was in his work, and material advancement was a secondary consideration. A man of strong imagination, he projected his ideas far ahead but was not led afield thereby.

At the time of his death, despite his 67 years, Dr. Wilson was still at the peak of scientific production. His passing is a tragic loss to microbiological science.

H. O. BUCKMAN

# FIXATION OF PHOSPHATE BY IRON AND ALUMINUM AND REPLACEMENT BY ORGANIC AND INORGANIC IONS<sup>1</sup>

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*Massachusetts Agricultural Experiment Station*

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Phosphate fixation has been the object of considerable study to develop practices that will increase the efficiency of applied phosphate fertilizers and of residual soil phosphates in crop production. The practices employed vary with the type of crop and the soil conditions and include application of the fertilizer in bands or strips, deep placement in the root zone, and pelleting of the fertilizer. These practices are based on the theory that the larger-sized particles or the zonal placement would expose less surface area of the fertilizer to the fixing agencies of the soil. Another practice which results in greater phosphate efficiency as reflected in better crop yields is the application of manure and phosphate together, as reported by Midgley and Dunklee (26). Reports indicate that the application of lime to acid soils causes an increase in available phosphate. Beneficial effects are also obtained by addition of sodium silicate to soils, but this practice has not been employed extensively.

These methods have proved to be of only limited success in preventing phosphate fixation, and there still remains a need for a practical method based on a better understanding of the process of fixation and the factors affecting it.

The purpose of this investigation was to determine the mechanism of phosphate fixation by compounds of iron and aluminum and to determine the ability of certain organic and inorganic anions to prevent the fixation of phosphate by these compounds. Numerous investigators (2, 7, 18, 25, 33, 39) have established that compounds of iron and aluminum are largely responsible for the fixation of phosphate in acid soils. An understanding of the mechanism by which phosphate is fixed by iron and aluminum would facilitate the development of more efficient agronomic practices to prevent it. Proof that the organic acids prevent fixation of phosphate by iron and aluminum would demonstrate the importance of organic matter in soil management and offer a practical means of reducing phosphate fixation.

## EXPERIMENTAL

### *Mechanism of phosphate fixation*

Many concepts have been advanced to explain the processes involved in the conversion of soluble phosphates to forms which are unavailable for plant use. Davis (6) groups these theories as follows:

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<sup>2</sup> Teaching fellow in agronomy, graduate student, and head of agronomy department, respectively. The work with aluminum was done by C. Vernon Cole in partial fulfillment of the requirements for the master of science degree. The work with iron was done by Richard M. Swenson in partial fulfillment of the requirements for the master of science degree.



1. Cations of soluble salts present in the soil, or cations replaced from the soil by those present in the solution, form precipitates with the phosphate ions. 2. By double decomposition, relatively insoluble soil minerals react to form insoluble phosphates. 3. Phosphates are absorbed at the extensive soil-solution interface. 4. Phosphates are absorbed by the soil minerals to form complex systems in one or more of the solid soil phases.

Microbiological consumption, chemical precipitation, and physicochemical absorption, according to Bear and Toth (1), are responsible for phosphate fixation in soils. Davis (6) tentatively concluded that phosphates may penetrate the liquid-solid phase interface and form new compounds with the hydrated minerals such as Werner coordination compounds. He named two conditions that may occur at the interface: (a) Hydroxyl groups oriented outward in a negative surface are replaced by phosphate ions, and (b) metal ions oriented outward react with phosphate ions.

Ionic exchange is the process believed responsible for phosphate fixation by Scarneth (34), Pugh and DuToit (30), and Ravikovitch (31). Anion-exchange reactions of soils have been described by Dean and Rubins (8) as the substitution of one anion on the exchange complex by another anion which is present in the soil solution in greater concentration or possesses a stronger tendency to hold its position on the exchange complex. These workers support the theory that soils have a definite anion-exchange capacity, and they believe that anion exchange is the mechanism causing much of the phosphorus retention of acid soils. On the other hand, Stout (37) theorized that phosphate fixation is a simple ionic exchange of phosphate ions for hydroxyl ions on the surface of the clay minerals.

Bear and Toth (1) have reported that in soils of high fixing capacity, such as Penn silt loam, which may fix the equivalent of 125 tons of 20 per cent superphosphate per 2 million pounds of soil, most of the phosphate is either saloid-bound or colloid-bound—the colloid-bound phosphate is replaceable by hydroxyl, humate, and silicate ions, and the saloid-bound phosphate by sulfate, chloride, citrate, and tartrate ions. Colloid-bound phosphate is considered an integral part of the colloidal micelles, while saloid-bound phosphate is present as  $\text{H}_2\text{PO}_4^-$  in the ion atmosphere surrounding the micelles. Karlson and Mattson (20) found that a high neutral salt concentration greatly reduced the amount of saloid-bound phosphate. This reduction in saloid-binding by the addition of neutral salts was originally reported by Gaarder (14) and is known as the "Gaarder effect."

The effects of certain anions on the precipitation of aluminum hydroxide found by Marion and Thomas (23) were explained on the basis of the formation of Werner type complexes with the hydrated hexa-aquocaluminum ion. They found that when standard aluminum solutions were titrated in the presence of strongly coordinating anions, less than the theoretical amounts of sodium hydroxide were needed to precipitate the aluminum completely. The trivalent aluminum ion was found to require only a little more than two equivalents of hydroxyl ion in the presence of anions that had a strong affinity for aluminum. They also found that when more than 1.00 millimole of citrate was added to 1.00 millimole of

aluminum, the aluminum was not precipitated by sodium hydroxide. The concentration of the added anion was shown to have definite effects on the pH value of maximum precipitation of the aluminum.

The authors carried out preliminary studies of the effects of the various anions on the precipitation of aluminum and ferric hydroxides by potentiometrically titrating aliquots of standard aluminum and iron solutions, of known free-acid content, in the presence of varying concentrations of phosphate and arsenate at room temperature. Since the coordination number of iron is 6, the hydrated ion can be considered as  $\text{Fe}(\text{H}_2\text{O})_6^{+++}$ . When hydroxyl ion is added to such a solution it has the ability to attract a hydrogen ion from three of the coordinatively bound water molecules. The following substances are therefore possible:  $\text{Fe}(\text{H}_2\text{O})_5(\text{OH})^{++}$ ,  $\text{Fe}(\text{H}_2\text{O})_4(\text{OH})_2^+$ , and  $\text{Fe}(\text{H}_2\text{O})_3(\text{OH})_3$ . The last is referred to in this report as "ferric hydroxide". Since the coordination number of aluminum is also 6, upon the addition of hydroxyl ion a similar series of substances is formed and in addition the aluminate ion,  $\text{Al}(\text{H}_2\text{O})_4(\text{OH})_2^-$ .

Stock solutions of ferric chloride and aluminum chloride containing a known excess of free hydrochloric acid were the source of iron and aluminum. The ferric chloride was prepared from reagent-quality salt, and the aluminum chloride solutions were prepared by dissolving metallic aluminum foil in an excess of hydrochloric acid. Both solutions were standardized according to the method given by Kolthoff and Sandell (21). A 0.20 N sodium hydroxide solution (carbonate-free) was prepared and standardized by an appropriate method. Potassium dihydrogen phosphate was the source of phosphate.

The titration curves of the pure aluminum and iron solutions containing 3.0 m.e. of these ions were first determined. The same amounts of aluminum and iron were titrated in the presence of 1, 3, and 9 m.e. of  $\text{KH}_2\text{PO}_4$ .<sup>2</sup> The titration of aluminum in the presence of  $\text{KH}_2\text{AsO}_4$  produced very similar titration curves. Data from the titration of aluminum and iron solutions under room conditions showed that the reaction proceeded to only 97 per cent of completion. Approximately two thirds as much sodium hydroxide was required to bring about complete precipitation of the iron and aluminum in the presence of excess phosphate or arsenate as in the absence of these anions. The pH value of maximum precipitation was lowered considerably by the presence of both phosphate and arsenate in a manner similar to that observed by Marion and Thomas (23) for organic anions. Davis and Farnham (5) reported that in the titration of aluminum solutions the equivalence point is not reached when titrating under room conditions, but that, when the solution is boiled after addition of NaOH, the resulting curve breaks at the equivalence point.

The influence of heat in bringing the reaction to completion was studied by adding increasing quantities of standard sodium hydroxide to a series of aliquots of standard aluminum and iron solutions containing 3.0 m.e. of these ions to which enough distilled water had been added so that the final volume was 100

<sup>2</sup> Since  $\text{KH}_2\text{PO}_4$  ionizes to give  $\text{K}^+$  and  $\text{H}_2\text{PO}_4^-$ , 1 m.e. is used to designate 0.001 of a molecular weight of this compound.



ml. The sodium hydroxide was added to the boiling solution with vigorous stirring, and heating was continued for one-half hour at the boiling point. The samples were then cooled and the pH value of each solution was determined with a Beckman pH meter. The titration curves constructed from values obtained by this method show a break at the theoretical equivalence point for both iron and aluminum solutions (figs. 1 and 2).

Under the conditions of the experiment 3.0 m.e. of NaOH was required completely to precipitate 3.0 m.e. of the ferric chloride or aluminum chloride from

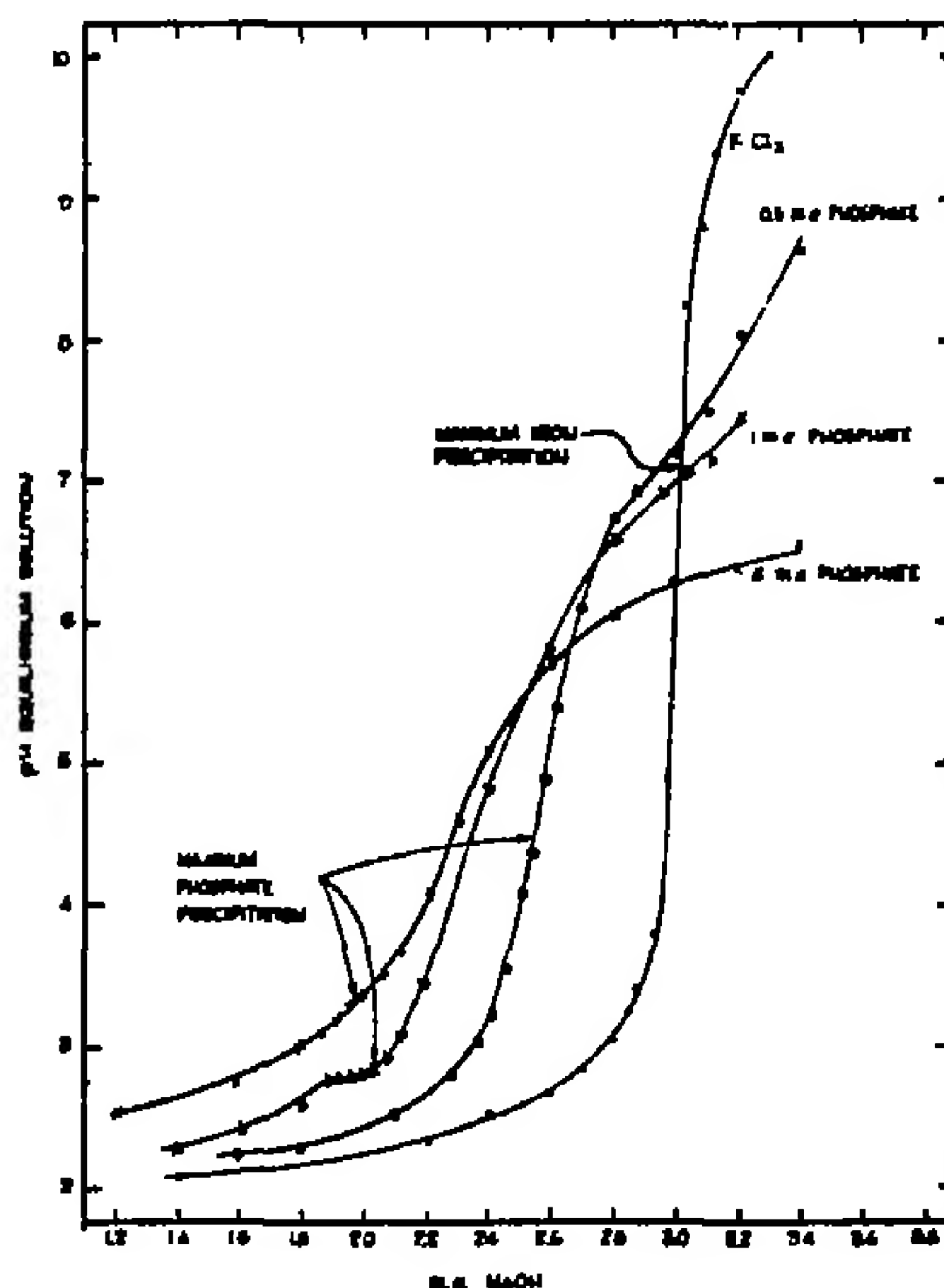


FIG. 1. POTENTIOMETRIC TITRATION OF  $\text{FeCl}_3$  WITH  $\text{NaOH}$  IN PRESENCE OF VARYING CONCENTRATIONS OF  $\text{KH}_2\text{PO}_4$ .

solution. When another ion is introduced that forms an insoluble precipitate with iron or aluminum, less NaOH is required for precipitation. The difference is equivalent to the precipitating power of the added ion. For example, if 1 m.e. of  $\text{KH}_2\text{PO}_4$  were added and the  $\text{H}_2\text{PO}_4^-$  occupied one of the coordinating positions on the iron or aluminum, only 2.0 m.e. of NaOH, or enough to fill the two remaining coordinating positions, would be required to reach the equivalence point. If the compound  $\text{FePO}_4$  or  $\text{AlPO}_4$  were formed when the phosphate was added, no NaOH would be required to induce precipitation. On the other hand, if the  $\text{HPO}_4^{2-}$  reacts with iron, two coordinating positions would be occupied and only 1.0 m.e. of NaOH would be required to reach the equivalence

point. These possibilities were investigated to determine the stoichiometric nature of the compounds formed.

The same heating procedure was used for the titration of iron and aluminum in presence of varying concentrations of  $\text{KH}_2\text{PO}_4$  as previously described for solutions without phosphate. When 0.5 m.e. of phosphate was added to a solution containing 3.0 m.e. of iron, 0.44 m.e. was combined and 2.56 m.e. of hydroxyl was required to reach the point of maximum precipitation of phosphate. When 1.0 m.e. of phosphate was added to the iron solutions, 0.88 m.e.

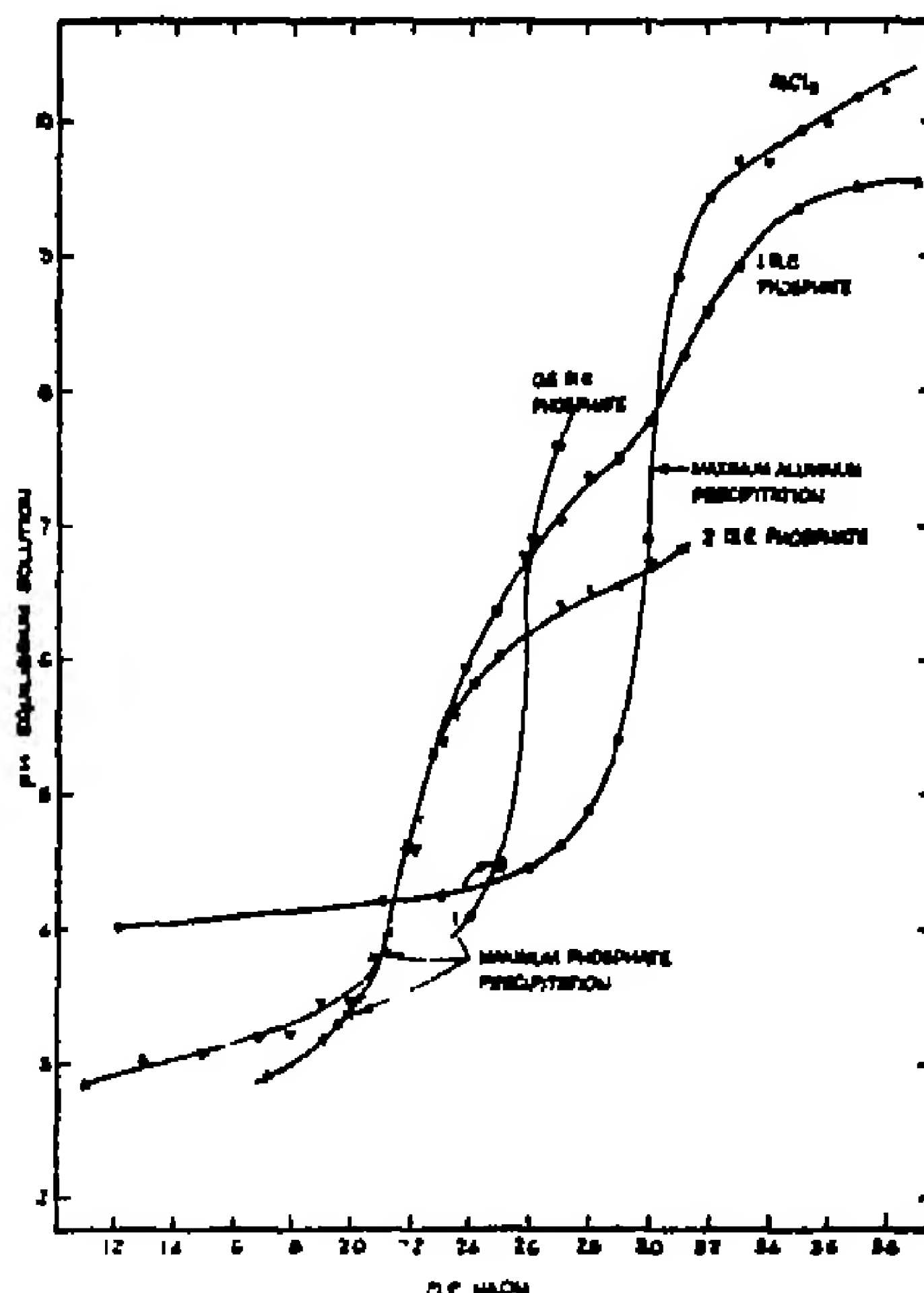
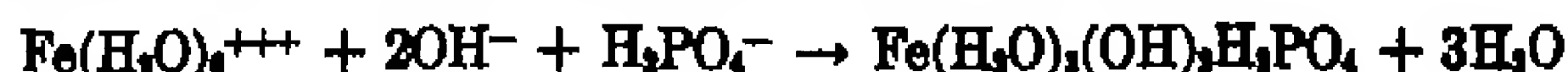


FIG. 2 POTENTIOMETRIC TITRATION OF  $\text{AlCl}_3$  WITH  $\text{NaOH}$  IN PRESENCE OF VARYING CONCENTRATIONS OF  $\text{KH}_2\text{PO}_4$

of phosphate was combined and 2.12 m.e. of hydroxyl was required to reach the point of maximum precipitation of the phosphate. When 3.0 m.e. of phosphate was added, the equivalence point was reached when 2.0 m.e. of hydroxyl had been added, as shown in figure 1. Analogous results were obtained with aluminum, as shown in figure 2.

These results indicate formation of the basic iron and aluminum phosphates,  $\text{Fe}(\text{H}_2\text{O})_5(\text{OH})_2\text{H}_2\text{PO}_4$  and  $\text{Al}(\text{H}_2\text{O})_5(\text{OH})_2\text{H}_2\text{PO}_4$ . In the pH range at which the reactions occurred, the predominant phosphate ion is  $\text{H}_2\text{PO}_4^-$ . The determinations of the amount of phosphate which was combined and the amount of

hydroxyl required for maximum precipitation indicate that  $\text{H}_2\text{PO}_4^-$  occupies one of the coordination positions of the hexahydrated iron or aluminum ions. Even when sufficient quantities of phosphate were added to occupy three of the coordination positions, only that amount combined which corresponded to the occupancy of one of the positions according to the reaction



*Reduction of saloid binding of phosphate by a neutral salt*

Analysis of the precipitates formed from solutions with a high ratio of phosphate to aluminum or iron showed that the amount of phosphate in the precipitate was in slight excess of the amount which can be accounted for by the stoichiometric combination of  $\text{H}_2\text{PO}_4^-$  with  $\text{Al}(\text{H}_2\text{O})_4(\text{OH})_2^+$  or  $\text{Fe}(\text{H}_2\text{O})_4(\text{OH})_2^+$ . This excess was believed to be due to adsorption effects and not to chemical combination.

Karlson and Mattson (20) reported that phosphate is held in two forms upon precipitation from aluminum solutions. Part of the phosphate was believed to be chemically combined with the aluminum in the formation of the colloidal micelles. The remainder was believed to be held by electrostatic attraction in the outer ion swarm of the colloid particles. Phosphate held in this manner was termed "saloid bound" since it is displaced by neutral salts.

The effect of neutral salt concentration upon the retention of phosphate by the aluminum and iron compounds was studied by analysis of precipitates obtained from solutions containing equivalent amounts of phosphate and aluminum or iron to which increasing amounts of sodium chloride had been added. The samples were precipitated under the same conditions as those in the previous determinations. One per cent of sodium chloride in solution was effective in preventing the saloid binding of phosphate, and higher concentrations of sodium chloride did not further reduce the amount of phosphate held by the precipitate. Sodium chloride was chosen as the neutral salt because the chloride ion shows only very slight tendency to coordinate with the iron or aluminum ions and because it was already present in the solution as a result of neutralization of the free HCl by NaOH. The phosphate held by aluminum and iron in the presence of 1 per cent NaCl is believed to be chemically combined with the aluminum and iron.

*Effect of pH on formation of basic iron and aluminum phosphates*

Numerous investigators (3, 11, 28, 32, 38) have shown that the amount of phosphate precipitated by iron and aluminum solutions and the fixation of phosphate by soils increase as the pH value of the solution or soil decreases. Teakle (38) and Davis (4) found that iron phosphate was least soluble at pH 3. Pugh (29) and Heck (16, 17) found that the isoelectric point of aluminum phosphate was higher than that of iron phosphate.

To determine the effect of pH on the chemical combination of  $\text{H}_2\text{PO}_4^-$  with iron and aluminum in the equilibrium solutions and the amount of phosphate

combined in the basic ferric phosphate and basic aluminum phosphate, a series of solutions containing 3.0 m.e. of iron or aluminum and 1.0 m.e. of phosphate were precipitated by addition of increasing quantities of NaOH with heating in the presence of neutral salt as previously described. Figure 3 shows the amount of phosphate fixed at the various pH values. The maximum fixation of phosphate occurred in the acid region of pH 2.5 to 3.5 for iron and 3.5 to 4.0 for aluminum. As the amount of phosphate in solution increased above that required to complete the reaction, the maximum precipitation of phosphate occurred at progressively higher pH values because of the buffering effect of the phosphate solution.

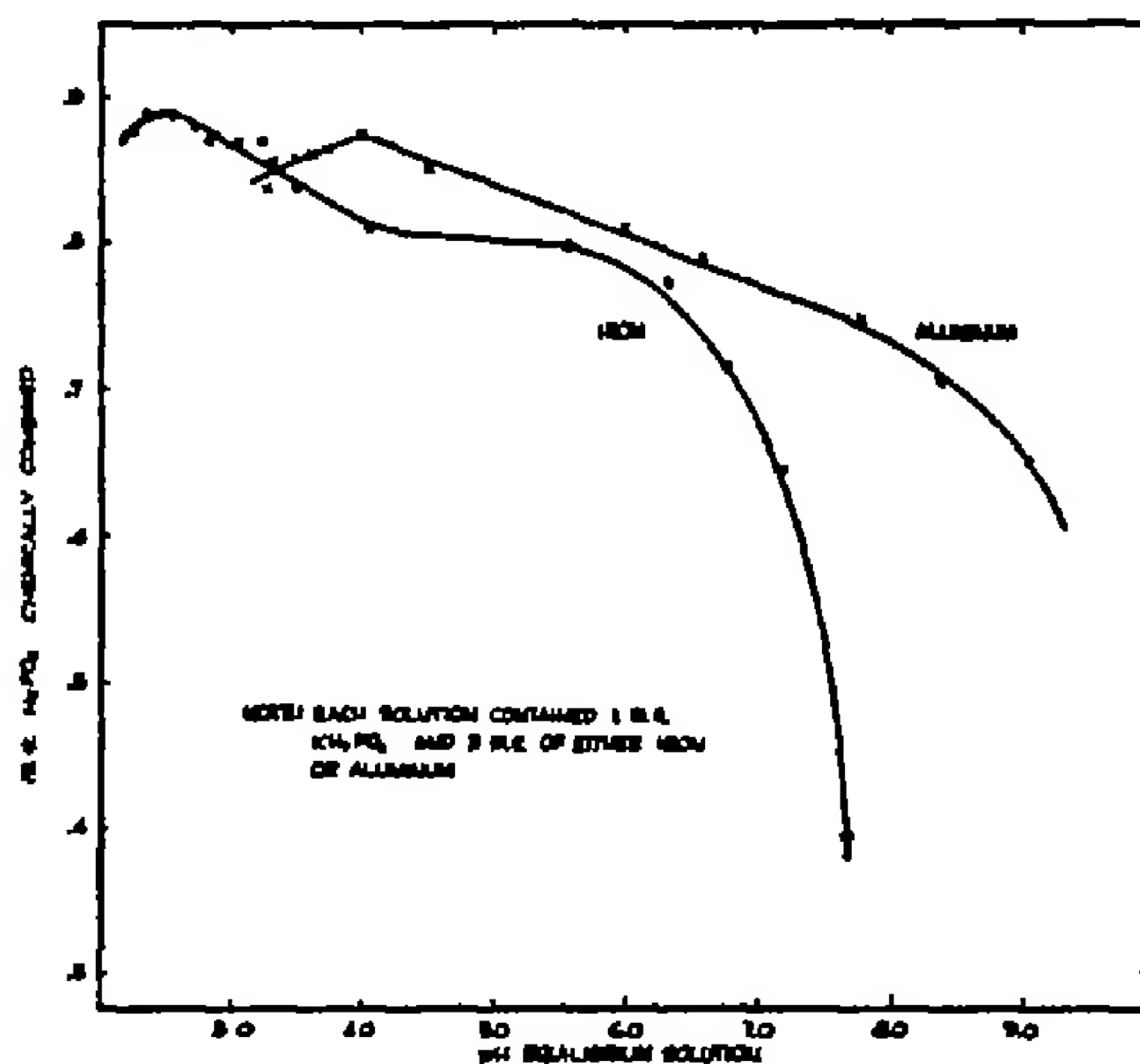


FIG. 3. EFFECT OF pH ON THE COMBINATION OF  $H_2PO_4^-$  WITH IRON AND ALUMINUM IN SOLUTION

Approximately 90 per cent of the phosphate was still fixed by iron and aluminum at pH 6.5, and 70 per cent was still fixed by aluminum at pH 9.0. As the pH value increased above 6.5 the replacement of  $H_2PO_4^-$  by  $OH^-$  from the iron compound was very rapid for the following reasons: (a) the stability of the  $Fe(H_2O)_5(OH)_2H_2PO_4$  decreases, (b) the  $H_2PO_4^-$  dissociates to form  $HPO_4^{2-}$ , and (c) the concentration of the  $OH^-$  increases, which shifts the equilibrium toward the formation of ferric hydroxide. These factors explain why iron is not so active in phosphate fixation above pH 6.5 as it is below that value. At pH 8.0 only 56 per cent of the fixed phosphate had been replaced from the iron by the  $OH^-$ , however, the rate of replacement was such that all the phosphate would be removed at approximately pH 8.5. With the basic aluminum phosphate,  $Al(H_2O)_5(OH)_2H_2PO_4$ , the tendency for increased  $OH^-$  to remove hydrogen from one of the coordinatively bound water molecules to form the aluminate ion is apparently greater than its tendency to replace  $H_2PO_4^-$  from the basic aluminum

phosphate. The phosphate thus remains chemically combined with aluminum at higher pH values than with iron.

Liming to increase the pH value of the soils with the subsequent release of fixed phosphate is a sound practice, but it is of limited value. Addition of enough lime to release 50 per cent of the phosphate chemically combined with iron and aluminum would necessitate raising the pH of the soil to between 7 and 8 for iron and even higher for aluminum.

These data indicate that the reacting phosphate ion is the  $\text{H}_2\text{PO}_4^-$ , since at the low pH of the reaction this ion would predominate rather than  $\text{HPO}_4^{--}$  or  $\text{PO}_4^{---}$ . This corresponds with the work of Davis (8), which shows that virtually no  $\text{PO}_4^{---}$  and only a very small amount of  $\text{HPO}_4^{--}$  exist in solution at pH values below 4.5.

#### *Determination of $\text{P}_2\text{O}_5/\text{R}_2\text{O}_3$ ratio*

The data obtained in the potentiometric titrations indicated that the reactions between iron and aluminum salts and phosphate ions at low pH values were chemical, producing the compounds  $\text{Fe}(\text{H}_2\text{O})_5(\text{OH})_2\text{H}_2\text{PO}_4$  and  $\text{Al}(\text{H}_2\text{O})_5(\text{OH})_2\text{H}_2\text{PO}_4$ . When a large excess of phosphate is added, it is theoretically possible for the  $\text{H}_2\text{PO}_4^-$  to occupy more than one coordinating position of either of these substances and thus produce compounds with  $\text{P}_2\text{O}_5/\text{Al}_2\text{O}_3$  or  $\text{P}_2\text{O}_5/\text{Fe}_2\text{O}_3$  ratios greater than unity. Progressively increasing amounts of phosphate were added to solutions containing 3.0 m.e. of iron or aluminum. At each phosphate concentration a series of solutions were used containing different quantities of NaOH to establish the pH of maximum phosphate precipitation.

The experimental procedure was the same as that described above except that the total volume of solution in each beaker was adjusted with distilled water to make the molar concentration of  $\text{KH}_2\text{PO}_4$  the same in all cases. Enough sodium chloride solution was added to make the final NaCl concentration 1 per cent. After the solutions had been boiled and cooled, and the pH determined, they were heated again to near boiling and filtered while hot. The precipitates were washed five times with hot 1 per cent sodium chloride solution to remove all phosphate that was not chemically combined with aluminum or iron. Five washings were found to be sufficient, and as many as twelve washings removed no more phosphate than did five. The phosphate that remained after this treatment was termed "chemically combined phosphate." The precipitates were dissolved in hot 1 per cent perchloric acid, and phosphate was determined according to the method of Sherman (35).

The maximum amounts of phosphate combined with iron and aluminum at various concentrations of phosphate are shown in table 1. It will be noted that the reaction did not go to completion until 2 m.e. of phosphate had been added for each 3.0 m.e. of iron or aluminum. Below that amount the concentration of  $\text{H}_2\text{PO}_4^-$  was not high enough to cause the reaction to go to completion. The results clearly indicate that both the  $\text{P}_2\text{O}_5/\text{Fe}_2\text{O}_3$  and  $\text{P}_2\text{O}_5/\text{Al}_2\text{O}_3$  ratios of the compounds formed were unity and that they did not exceed that value even though 9.0 m.e. of phosphate was added for each 3.0 m.e. of iron or aluminum. They also indicate a chemical reaction rather than a simple adsorption process.

The titration curves and the pH of maximum precipitation have shown that it is the  $H_2PO_4^-$  rather than the  $HPO_4^{--}$  or  $PO_4^{---}$  that reacts with the iron and aluminum, whereas these data show that, regardless of the amount of excess phosphate added, only one of the coordinating positions of the iron or aluminum is occupied by the  $H_2PO_4^-$ . Thus, along with the fact that 2.0 m.e. of  $OH^-$  and 1.0 m.e. of  $H_2PO_4^-$  were required for precipitation of 3.0 m.e. of iron or aluminum, shows conclusively that the compounds formed under the conditions of this experiment were  $Al(H_2O)_3(OH)_2H_2PO_4$  and  $Fe(H_2O)_3(OH)_2H_2PO_4$ .

*Replacement of chemically combined phosphates by various anions*

Many analytical procedures for determining replaceable phosphate in soils are based on use of salts of organic and inorganic anions. Dean and Rubins (8) have compared the effectiveness of fluoride, citrate, tartrate, arsenate, and acetate for removing adsorbed soil phosphorus. Kurtz, DeTurk, and Bray (22)

TABLE 1  
*Influence of phosphate concentration on composition of basic iron and aluminum phosphates*

PHOSPHATE ADDED	IRON OR ALUMINUM	PHOSPHATE CHEMICALLY COMBINED IN BASIC PHOSPHATE	
		Iron	Aluminum
m.e.	m.e.	m.e.	m.e.
0.5	3.0	0.448	0.460
1.0	3.0	0.880	0.860
1.5	3.0	0.956	0.942
2.0	3.0	0.995	0.981
3.0	3.0	0.997	0.985
4.0	3.0	0.997	
6.0	3.0	1.007	0.988
9.0	3.0	0.981	0.983

found that various anions replaced adsorbed phosphate in the following order: fluoride, oxalate, citrate, bicarbonate, borate, acetate, thiocyanate, sulfate, chloride. The borate, acetate, thiocyanate, sulfate, and chloride removed amounts similar to or smaller than the amounts removed by water. Demolon and Bastisse (9) observed that less phosphate is absorbed from a mixture with another absorbable ion, such as tartrate, citrate, oxalate, and silicate, than from a mixture with a nonabsorbable anion such as  $Cl^-$ ,  $SO_4^{--}$ , and  $NO_3^-$ . They further established that phosphate fixed by the soil could be removed more easily by a salt of an absorbable ion than by one of a nonabsorbable ion.

Marion and Thomas (23) showed that certain anions which have a high coordinating affinity for aluminum prevented precipitation of the aluminum as the hydroxide. Citrate and tartrate were particularly effective, whereas sulfate, chloride, and nitrate had little effect. Graham and Thomas (15) studied the neutralization of various acids by hydrous alumina and concluded that the rate of reactivity was dependent upon the stability of the alumino-anion complex formed. Those forming stable complexes reacted more actively than those



that did not form stable complexes with aluminum. The results of these investigations indicate that organic acids having the ability to form complexes with iron and aluminum would be effective in replacing fixed phosphate.

Heck (16), Weiser (41), Jensen (19), Midgley and Dunklee (26), and many others found that organic matter reduced the amount of phosphorus fixed by certain acid soils. Metzger (24) believed that active iron would be reduced in the presence of organic matter, thus making the phosphate more available. Scarso (34) suggested that increased availability of phosphate was due to the fact that iron is tied up by the carbon dioxide produced by decaying organic matter or that the humates replace the phosphate held by the iron and aluminum. The effectiveness of organic matter in preventing phosphate fixation in the soil according to Sierling (36), is related to occupancy of the coordinated valences of the aluminum by organic anions that are not replaced by the active phosphate ions.

The authors believe that the increased availability of phosphate in the presence of organic matter, noted by several investigators, is caused by the organic acids formed as decomposition products. The organic anions may coordinate with iron and aluminum to form complexes more stable than the basic iron phosphate or basic aluminum phosphate and thus release phosphate to the soil solution. These organic anions may also fill the coordinating valences of the iron and aluminum and thus prevent formation of the basic iron or aluminum phosphates. An experimental procedure was adopted to determine the ability of certain anions to replace fixed phosphate and to determine a lyotropic series of anions according to their phosphate-replacing ability. The same technique as previously used in the determination of the  $P_2O_5/Al_2O_3$  and  $P_2O_5/Fe_2O_3$  ratios was employed using 3 m.e. of iron or aluminum and 1 m.e. of phosphate, except that organic acids or organic salts adjusted to the proper pH were added in increasing quantities. Fluoride, silicate, and arsenate were also used.

The results show that several of the anions studied have the ability to prevent fixation of phosphate by iron and aluminum and that the amount of phosphate replaced varied with the nature and concentration of the anion. Figure 4 shows the relative ability of various organic and inorganic ions to replace phosphate from basic iron phosphate at pH 3.4, and figure 5 shows similar data for aluminum at pH 3.8.

The effectiveness of the anions in replacing phosphate is related to their ability to coordinate with iron and aluminum and thus to the nature of the complex formed. Certain organic acids are therefore able to prevent fixation of phosphate by iron and aluminum, and other organic acids may possess the same chemical ability. The relative effectiveness of the various anions changed with variation of the pH value of the solutions. An increase of the pH value from 3.4 to 6.3 increased the effectiveness of citrate and decreased the effectiveness of tartrate, while that of fluoride remained practically constant. The increase with citrate was greater than could be attributed to the additional hydroxyl alone. Investigations are being conducted in this laboratory to determine the

influence of pH on the relative ability of the various anions to prevent phosphate fixation.

Since the properties of  $\text{H}_2\text{PO}_4^-$  and  $\text{H}_2\text{AsO}_4^-$  are similar and since they are both the predominating form of the acids in solutions of pH value from 3 to

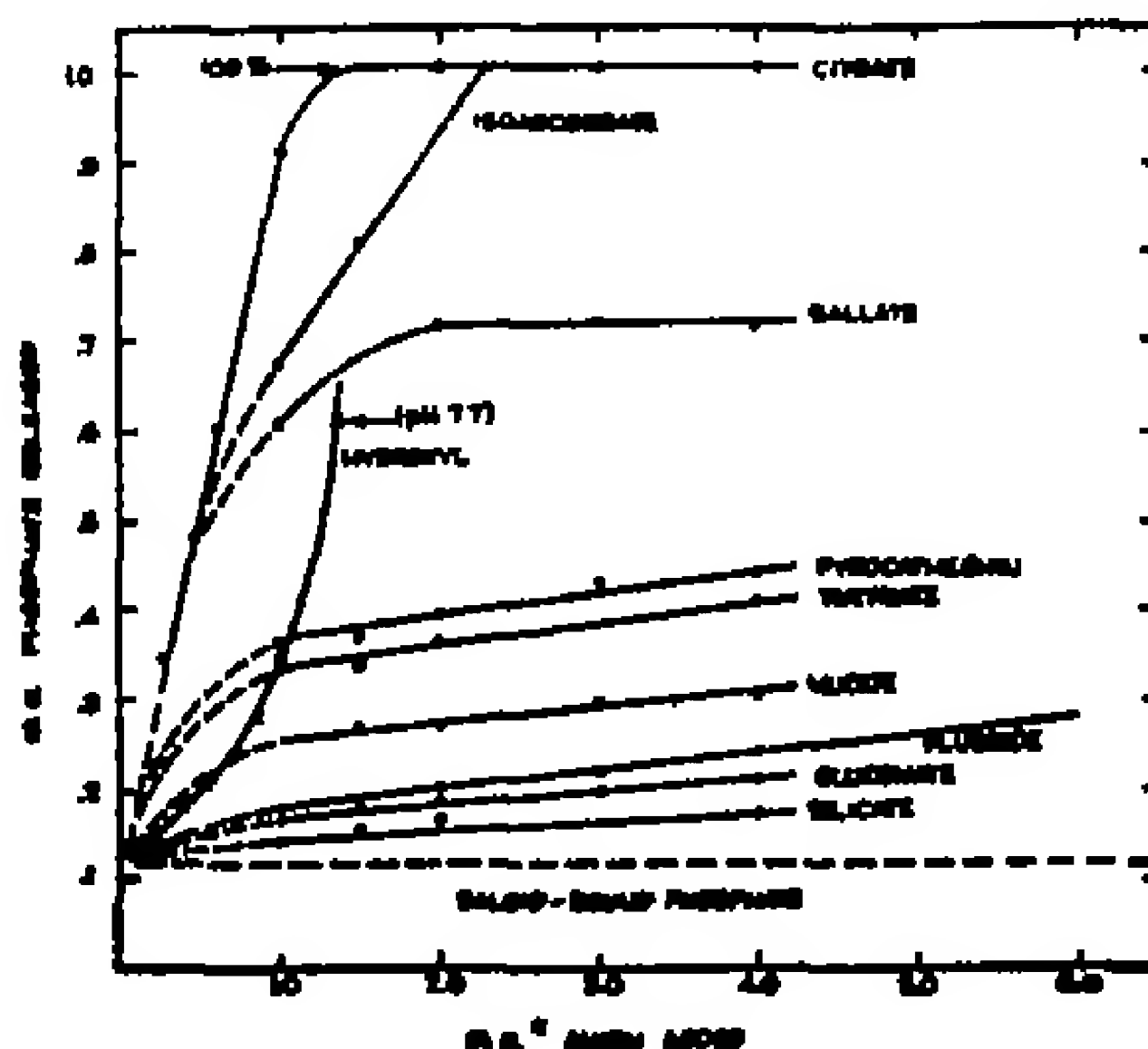


FIG. 4. ABILITY OF VARIOUS ANIONS TO RELEASE CHEMICALLY COMBINED PHOSPHATE FROM BASIC IRON PHOSPHATE

\* The equivalent weight of all anions taken as 1 molecular weight except for tartrate, the equivalent weight which was taken as 0.5 molecular weight

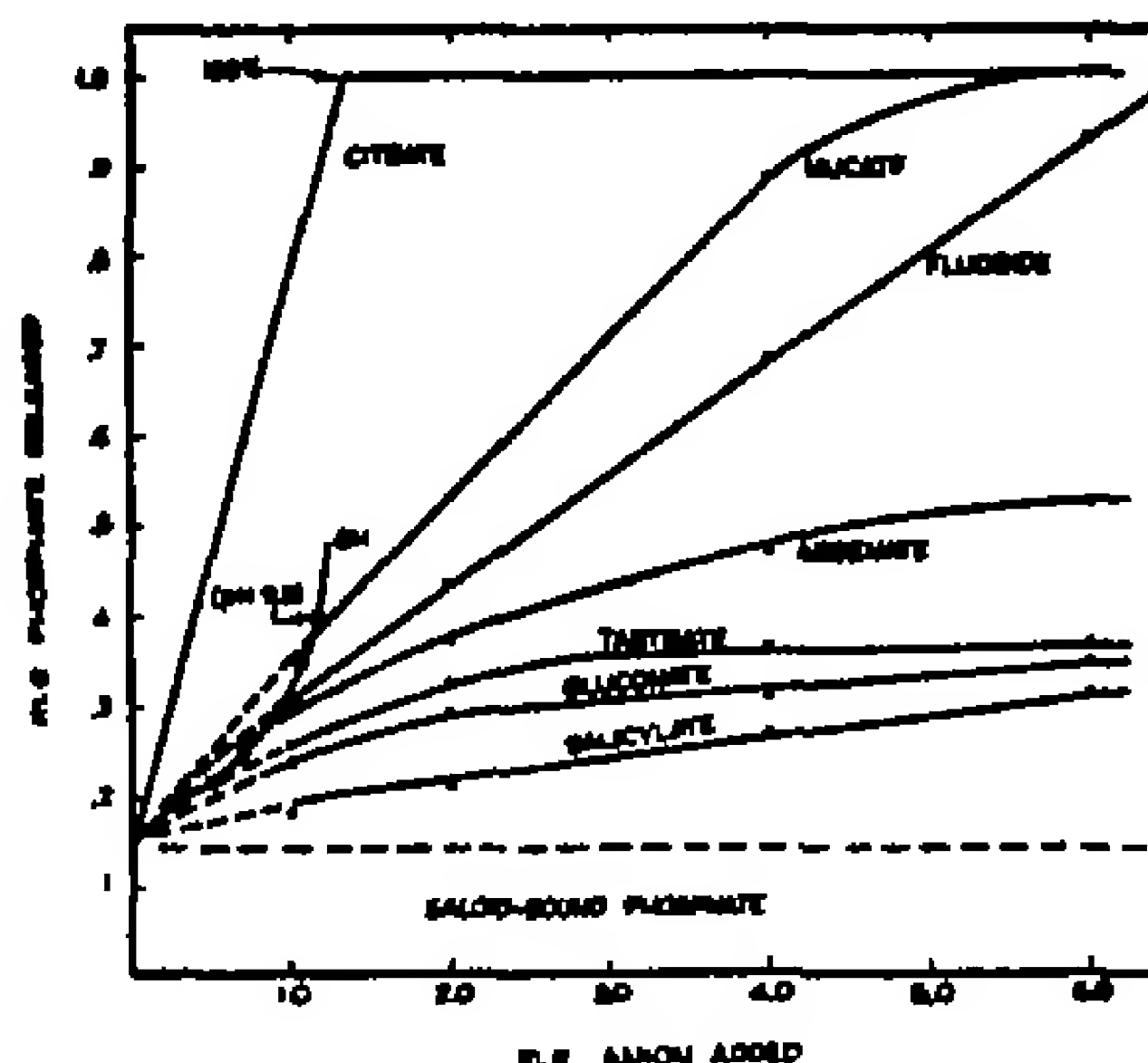


FIG. 5 ABILITY OF VARIOUS ANIONS TO RELEASE CHEMICALLY COMBINED PHOSPHATE FROM BASIC ALUMINUM PHOSPHATE

5, their reactions with aluminum were expected to be of the same nature. The reaction with arsenate was studied to determine the relative stability of the basic aluminum arsenate and phosphate. The pH of maximum precipitation was found to be essentially the same for basic aluminum arsenate and for basic



aluminum phosphate; however, with phosphate the reaction was complete upon addition of 2.0 m.e. of phosphate, but with arsenate the reaction was only 78 per cent complete, even upon the addition of 4.0 m.e. of arsenate, indicating a greater stability of the basic aluminum phosphate than of the basic aluminum arsenate.

To study the relative replacing abilities of phosphate and arsenate, a series of solutions containing 3 m.e. of aluminum were precipitated in the presence of varying amounts of phosphate and arsenate under the same conditions of precipitation used in the study of the individual reactions. One series of samples was prepared containing 1.0 m.e. of  $\text{H}_2\text{PO}_4^-$  and increasing amounts of  $\text{H}_2\text{AsO}_4^-$ . A second series was prepared containing 1.0 m.e. of  $\text{H}_2\text{AsO}_4^-$  and increasing amounts of  $\text{H}_2\text{PO}_4^-$ . Table 2 shows the amounts of each anion held by the precipitate after filtration and washing. The percentage replacement of phosphate

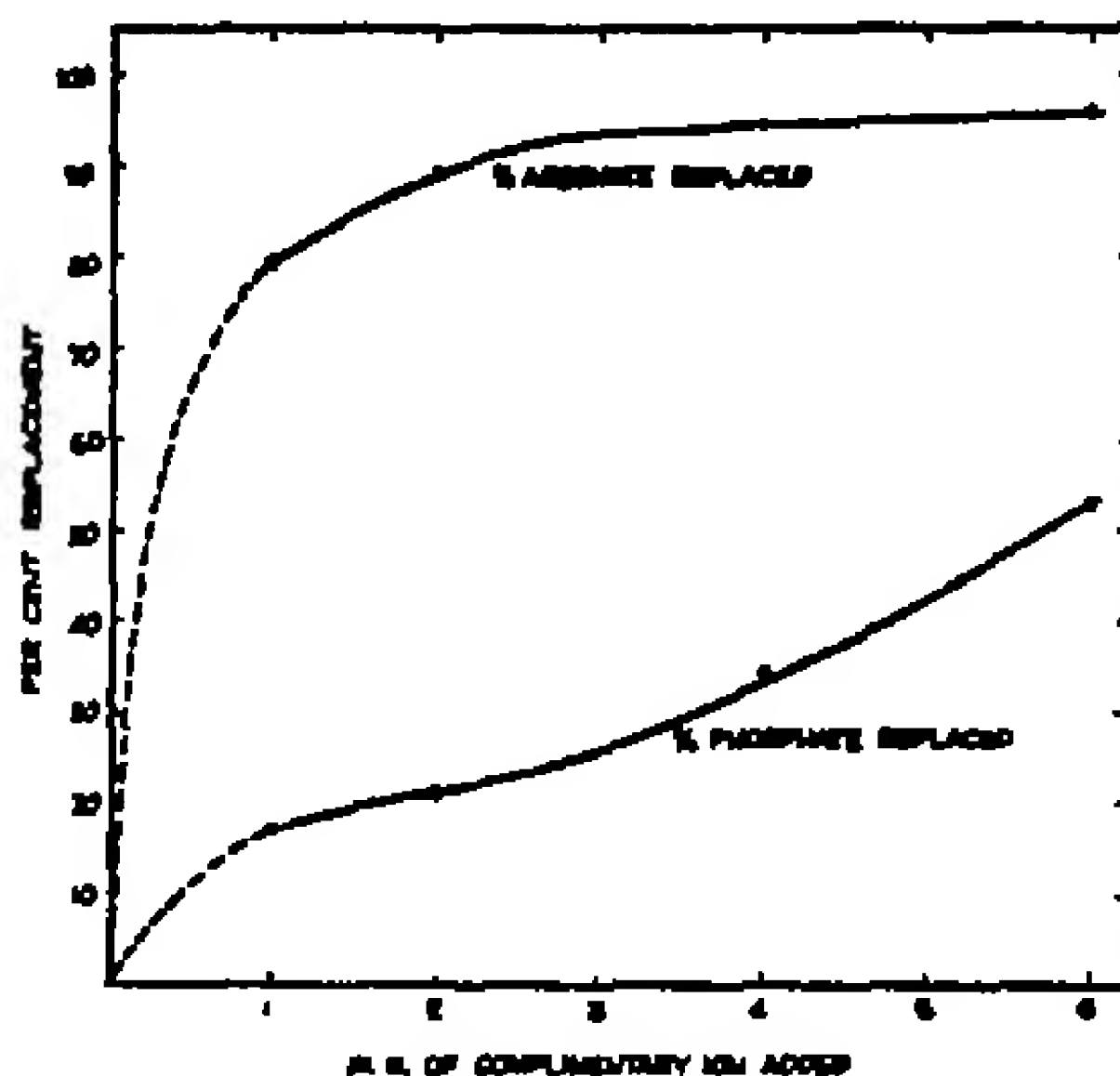


FIG. 6 REPLACEMENT OF ARSENATE BY PHOSPHATE AND OF PHOSPHATE BY ARSENATE

by arsenate and that of arsenate by phosphate is shown in figure 6. The percentage replacement was calculated on the basis that 0.86 m.e. of phosphate and 0.70 m.e. of arsenate were held by 3.0 m.e. of aluminum when the replacing anion was not present. These data indicate that at equal concentrations the ability of phosphate to replace arsenate is approximately five times as great as the ability of arsenate to replace phosphate.

Samples of electrodialed humus and lignin were employed in the same manner as the organic acids to determine their effectiveness in preventing the chemical combination of phosphate with iron. Since the equivalent weights of these two substances are not known, weighed quantities rather than milliequivalents were used. The same techniques were employed as with the soluble organic anions. The results, shown in figure 7, are not comparable with those obtained for soluble organic compounds but do show that both of these substances have a definite capacity for preventing phosphate from combining with iron and probably with aluminum.

Fixation of phosphate by soil minerals and its replacement by various anions

Information obtained from study of solutions of iron and aluminum was applied to study of phosphate fixation by soil minerals Ford (13), Weiser (41) and others (3, 16, 24) have shown that the hydrous oxides of iron fix phosphorus. It has also been shown by Perkins and King (28) that grinding the iron compound to reduce particle size increases the phosphate fixing capacity

TABLE 2  
Relative replacing abilities of  $H_2PO_4^-$  and  $H_2AsO_4^-$

ANIONS ADDED PER SAMPLE		ANIONS REPRECIPITATED		
$H_2PO_4^-$	$H_2AsO_4^-$	$H_2PO_4^-$	$H_2AsO_4^-$	Total
m.e.	m.e.	m.e.	m.e.	m.e.
1 00	1 00	0 71	0 12	0 83
1 00	2 00	0 68	0 17	0 85
1 00	4 00	0 56	0 32	0 88
1 00	6 00	0 41		
1 00	1 00	0 73	0 16	0 89
2 00	1 00	0 93	0 08	1 01
4 00	1 00	1 01	0 04	1 05
6 00	1 00	1 06	0 03	1 09

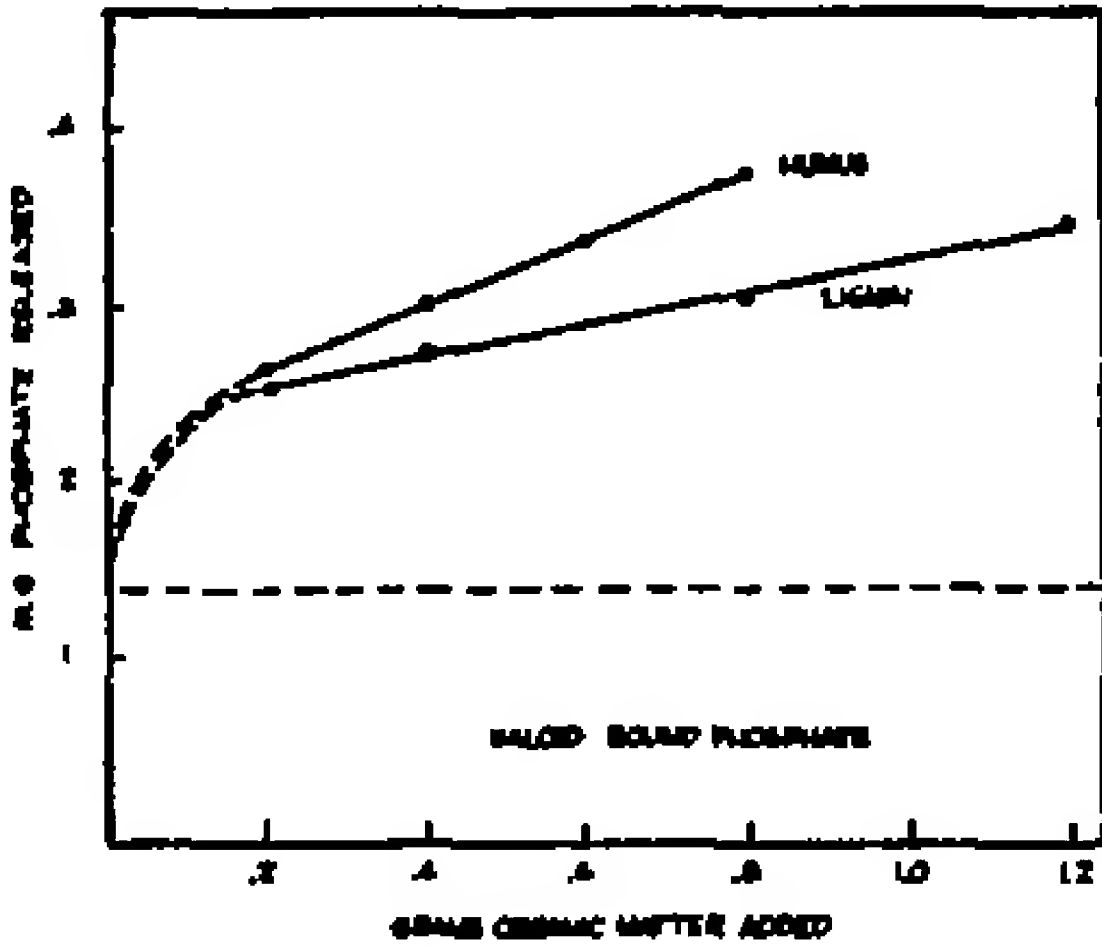


FIG 7 ABILITY OF HUMUS AND LIGNIN TO PREVENT PHOSPHATE FIXATION

Samples of limonite<sup>4</sup> ( $2Fe_2O_3 \cdot 3H_2O$ ) and Goethite ( $Fe_2O_3 \cdot H_2O$ ) were crushed and then ball-milled for 15 days These samples were phosphated with a solution of  $KH_2PO_4$  at pH 3.4 by boiling for approximately 5 hours The excess phosphate was removed by filtration and repeated washings with 1 per cent NaCl solutions. The amount of chemically combined phosphate was determined by replacing it with boiling 0.2 N NaOH and was found to be 1.28 m.e. for each gram of phosphated limonite and 1.09 m.e. per gram of phosphated Goethite

<sup>4</sup> The limonite and Goethite were obtained from Ward's Natural Science Establishment, Rochester, New York.

Three series of phosphated mineral samples were treated with increasing quantities of citric and gallic acids and with sodium fluoride at pH 3.4. Figure 8 shows the ability of citrate, fluoride, and gallic acid to replace fixed phosphate from phosphated Goethite. Comparable results were obtained with limonite. The order of replacement of the anions tested is similar to that obtained when the soluble salt of iron was used in the reaction. This indicates that insoluble hydrous oxides are effective in phosphate fixation, and that since the replacement of the combined phosphate by other anions followed the same general pattern, the fixation is likely a chemical combination similar to that suggested for the reaction between phosphate and iron in solution.

One of the authors (36) previously reported that the active constituent of ball-milled kaolin in phosphate fixation was a hydrated alumina which had been

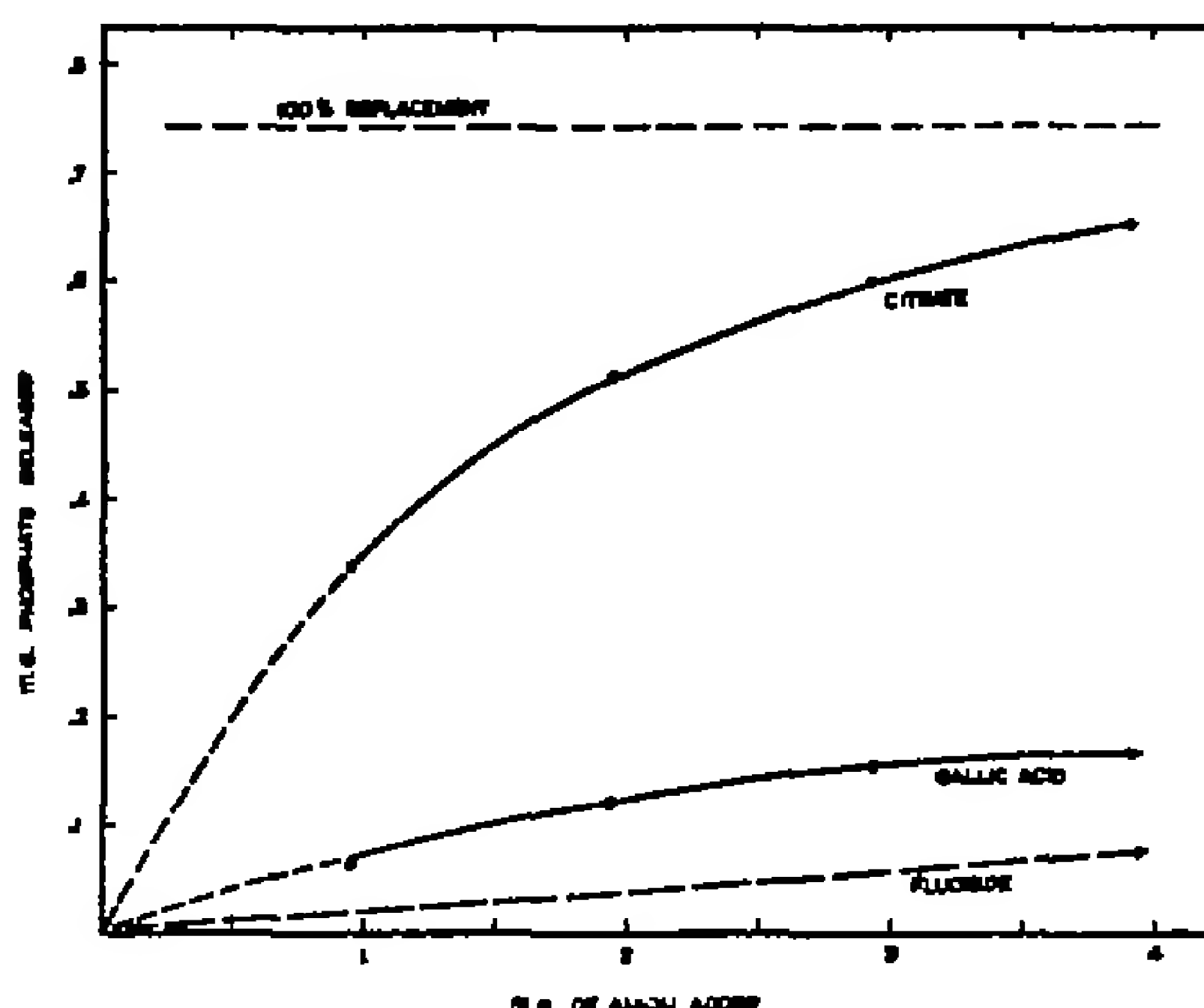


FIG. 8. ABILITY OF CITRATE, FLUORIDE, AND GALLIC ACID TO RELEASE FIXED PHOSPHATE FROM PHOSPHATED GOETHITE

released from the aluminosilicate in the grinding. This statement was based on the observation that the active constituent of ball-milled kaolin is removed by extraction with 0.1 *N* HCl and 0.1 *M* tartaric acid. Other investigators (10, 27, 37) have suggested that kaolin fixes phosphate by ionic replacement of terminal and exposed OH groups in the crystal lattice.

Samples of ball-milled kaolin were phosphated, and the ability of various anions to replace this combined phosphate was determined in a manner similar to that previously described for the iron minerals. It was found that 1 gm. of phosphated kaolin contained 2.4 m.e. of "saloid" and "chemically combined phosphate," and that 0.43 m.e. could be removed by salt solution, leaving 1.97 m.e. chemically combined. A quantity of phosphated kaolin representing 0.82 m.e. of chemically combined phosphate and 0.18 m.e. of saloid-bound phosphate was used to determine the relative effectiveness of various anions in replacing

phosphate. Samples of phosphated kaolin were treated with increasing quantities of citrate and fluoride. The amounts of phosphate replaced are shown graphically in figure 9. Citrate was very effective at low concentrations, whereas complete replacement of phosphate by fluoride did not result until 6 m.e. of fluoride for each milliequivalent of phosphate had been added. This corresponds to the data obtained when aluminum solutions were used (fig. 4). When the

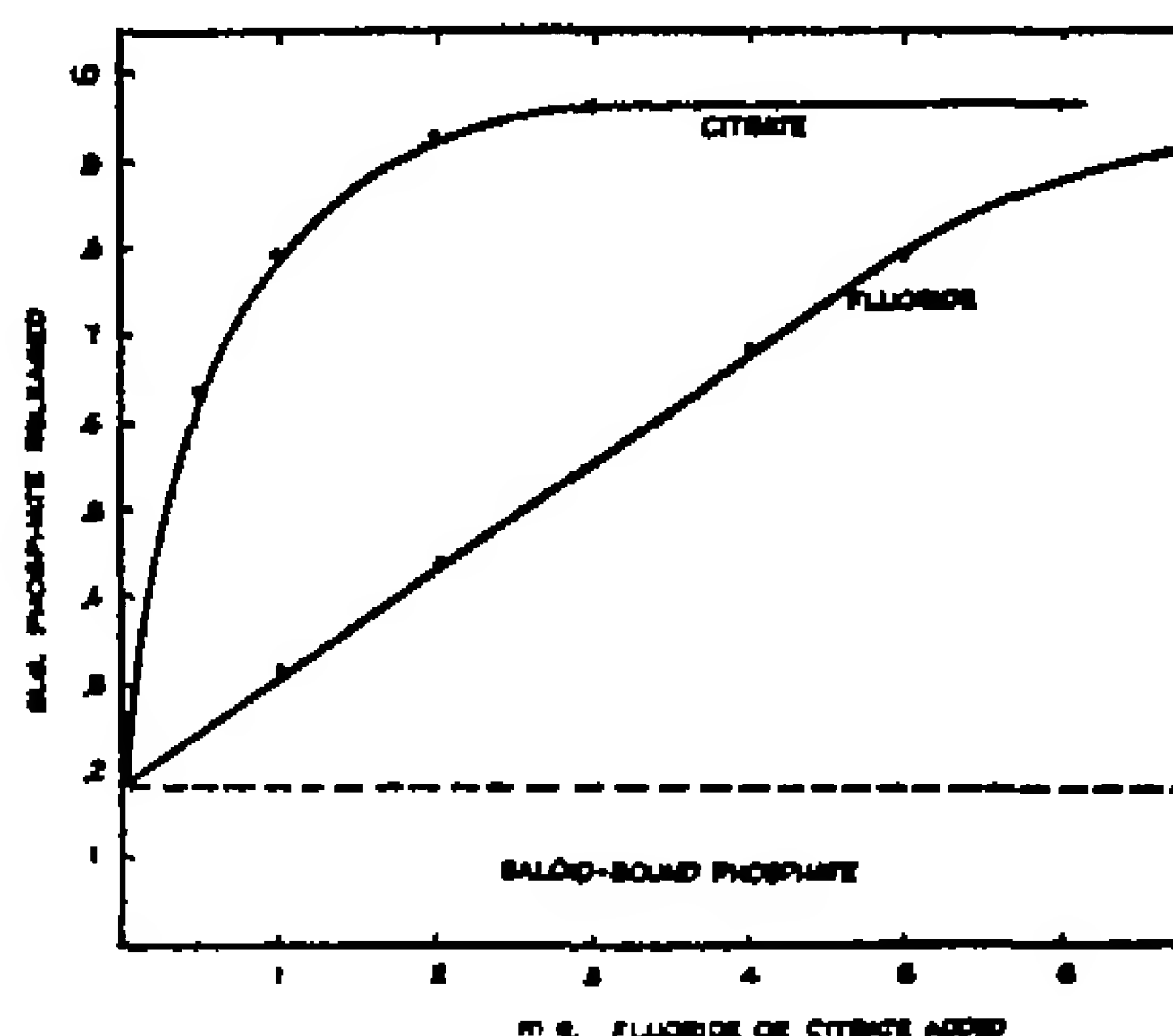


FIG. 9. EFFECTIVENESS OF CITRATE AND FLUORIDE IN RELEASING PHOSPHATE FROM PHOSPHATED KAOLIN

TABLE 3

*Replacement of phosphate and aluminum from phosphated kaolin by citrate\**

Citrate added	m.e.	0.5	1.0	2.0	3.0	6.0
Equilibrium pH		3.95	3.8	3.77	3.70	3.50
Phosphate replaced	m.e.	0.63	0.80	0.92	0.97	0.97
Aluminum replaced†	m.e.	0.43	0.63	0.73	0.80	0.80
Difference between phosphate and aluminum replaced	m.e.	0.20	0.17	0.19	0.17	0.17

\* 0.4173-gm. samples were used. Each sample contained 0.18 m.e. colloid-bound phosphate and 0.82 m.e. colloid-bound phosphate.

† 1 m.e. Al is 1 millimole of Al and the amount which will react with 1 m.e. of phosphate at pH 3.8.

phosphate was replaced from phosphated kaolin by fluoride, the extracts contained negligible quantities of aluminum. Fluoride has a high coordinating ability with the aluminum ions, therefore, a stable basic aluminum fluoride,  $\text{Al}(\text{H}_2\text{O})_5(\text{OH})_2\text{F}$ , is precipitated when solutions of fluoride and aluminum ions are titrated with sodium hydroxide. This reaction is analogous to the formation of basic aluminum phosphate. Fluoride replaces phosphate from the basic aluminum phosphate in concentrations in which the fluoride is less than six times the aluminum. In these cases, titration curves indicate that only one coordinating position of the aluminum is occupied by either fluoride or phos-

phate, however, when the fluoride is present in a concentration greater than 6.0 m.e. per millimole of aluminum, the hexafluoride complex is formed and the aluminum dissolves, bringing about a complete release of the phosphate.

When the phosphate was replaced from the "phosphated kaolin" by citrate it was observed that the extracts contained appreciable quantities of aluminum. The amounts of aluminum in these extracts along with the amount of phosphate replaced by the citrate are listed in table 3. The amount of phosphate replaced in each instance exceeds the aluminum in solution by an approximately constant quantity. The difference coincides with the amount of saloid-bound phosphate normally replaced by a salt solution which does not remove appreciable quantities of aluminum. It seems likely that the effectiveness of citrate in replacing phosphate from "activated kaolin" results from the complexing and dissolving of aluminum by the citrate.

These data indicate conclusively that the effective constituent in ball-milled kaolin is a hydrous aluminum oxide which will react with phosphate to form an insoluble hydrated basic aluminum phosphate, or with citrate to form a soluble aluminum citrate complex, the latter being more stable under the conditions of the experiments conducted.

#### DISCUSSION

Citrates, tartrates, and other organic anions have been employed extensively as analytical reagents in determining so-called available phosphates in soils. It is believed that the ability of these organic acids to extract phosphate from soils is due to their property of forming stable complexes with iron and aluminum. Ephraim (12) has enumerated certain characteristics of organic acids that are required for them to form complex ions with metals. These characteristics are (a) The radical must contain an acidic group which can take up one of the primary valences of the metal in salt formation, (b) groups must be present which can become coordinated with the central atom through their lone pair of electrons, and (c) these last radicals must be separated from the replaceable H atom by chains of suitable length for the production of five-membered or six-membered rings.

When acids possessing these characteristics were employed to replace chemically combined phosphates from basic iron and aluminum phosphates, they were found to replace significant quantities but varied considerably in their effectiveness. The stability of the complex formed with the organic anion, compared with the stability of the basic aluminum or iron phosphates, determines the ability of the anion to replace phosphate. Although the amino acids used experimentally in this investigation were ineffective in complexing the iron and aluminum and thus preventing phosphate fixation, it is believed that the amino acids might be more effective at higher pH values, since at the lower pH values the amino group acts as a hydrogen acceptor, thus preventing chelation. It was shown in this investigation that increasing the pH value would change the order of replacement of phosphate by the various anions—with an increase in pH the amino acids might become very effective. In the soil these amino acids

are converted rather readily to the corresponding hydroxy acids in the process of deamination by bacteria, and the resulting hydroxy acid should be effective in forming complex compounds with iron and aluminum.

Midgley and Dunklee (26) have reported that organic matter from manure makes added phosphate more available when the phosphate is incorporated in the manure than when the manure and phosphate are applied to the field separately. The ability of organic matter to prevent phosphate fixation has been attributed to the reduction of iron compounds by bacteria, the replacement of the phosphate in the colloidal complex by humus, and the conversion of the phosphate to organic phosphorus compounds. Humus and lignin are known to contain functional groups which could be efficient in forming stable complexes with both iron and aluminum. Both of these substances were active in replacing chemically combined phosphate from the basic aluminum and iron phosphate compounds. The value of organic matter in soils takes on an added significance because of its effectiveness in preventing added phosphate from being chemically combined with iron and aluminum and because it releases combined phosphate by the formation of stable iron and aluminum complexes. This would be particularly true under conditions where the organic matter was being actively decomposed with the production of organic acids that are efficient in this process.

Certain inorganic anions are also effective in preventing phosphate fixation and replacing chemically combined phosphates. Arsenates and fluorides were found to be somewhat less capable than certain of the organic acids. Under conditions of identical concentrations of arsenate and phosphate, the phosphate was about five times as effective in replacing arsenates as the arsenate in replacing phosphate from the chemically combined form. Those organic acids which were more effective in replacing phosphate than was arsenate would then be very efficient in replacing arsenate. Soils containing large quantities of chemically combined arsenate as either basic aluminum or basic iron arsenates could be practically reclaimed by treatment with large quantities of phosphate or organic matter producing these active organic anions. This would cause the displacement of arsenate to lower horizons where it would not be so detrimental to the shallow-rooted crops.

The use of cryolite for reclaiming arsenated soils has been suggested, and its action may be explained by the reaction of the aluminohexafluoride ion of the cryolite with the basic aluminum arsenate to replace the arsenate and form basic aluminum fluoride. In regions where fluorides are known to be deficient in soils and water supplies, and where as a result of this the incidence of dental caries is great, it seems conceivable that applications of soluble fluorides as a soil amendment might be of value in replacing the chemically combined phosphate and in turn increasing the fluoride content of the water supply and of the crops grown on the soils.

Many methods have been devised for determining so-called available phosphate in agricultural soils. A varied assortment of extracting solutions has been used for removing the available phosphorus for determination. Since the avail-



able phosphate is most accurately measured by crop performance, those methods which extract phosphate from the soil in amounts similar to that removed by cropping are considered most reliable. The saloid-bound phosphate or that phosphate which is sorbed by soil colloids and which can be removed by salts or dilute acids is considered available to the growing crop. The method of Truog (40), which gives values corresponding very well with those obtained by plant growth, is a typical example of a method which extracts only saloid-bound phosphate. Methods employing the use of citrates, tartrates, fluorides, arsenates, and other anions which are capable of replacing the chemically combined phosphates by forming stable complex ions or compounds with iron or aluminum, liberate much more phosphate than would be obtained by the crop.

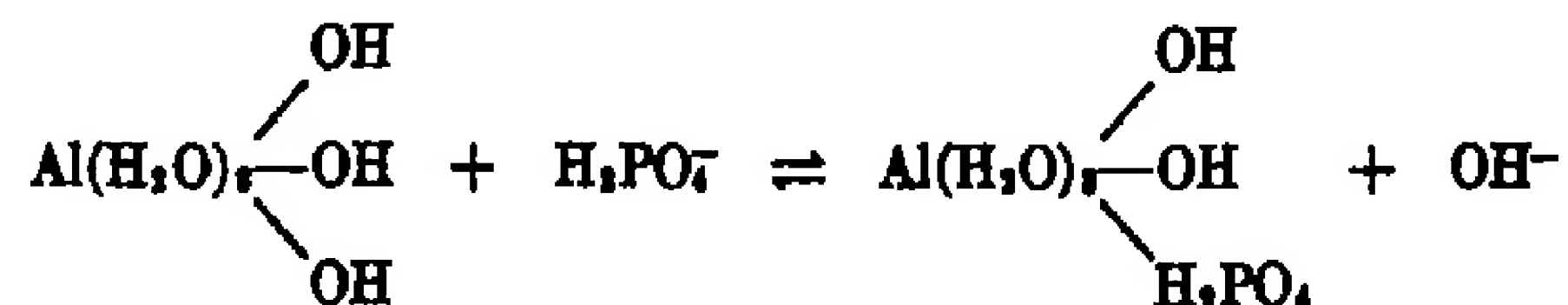
#### SUMMARY AND CONCLUSIONS

Potentiometric titrations of iron and aluminum chlorides in the presence of phosphate showed inflection points in the titration curves which indicated that for each metal ion, two hydroxyls and one phosphate ion reacted to give a basic phosphate represented by the formulas  $\text{Al}(\text{H}_2\text{O})_3(\text{OH})_2\text{H}_2\text{PO}_4$  and  $\text{Fe}(\text{H}_2\text{O})_3(\text{OH})_2\text{H}_2\text{PO}_4$ .

The pH of maximum precipitation of basic iron phosphate was 2.5 to 3.5, whereas for basic aluminum phosphate it was from 3.5 to 4.0. This is the pH range at which  $\text{H}_2\text{PO}_4^-$  predominates and where there is relatively little  $\text{HPO}_4^{--}$  and virtually no  $\text{PO}_4^{---}$ . This indicates that the  $\text{H}_2\text{PO}_4^-$  is the phosphate ion which reacts to form chemically combined phosphate.

The amount of phosphate which would combine chemically with one iron or aluminum ion increased as the phosphate increased, to a value where one phosphate was combined with one iron or one aluminum ion, and two hydroxyls were required to complete the precipitation. In no instance was the ratio of phosphate to iron or aluminum in the precipitated compound greater than unity even when the amount of phosphate present was nine times that of the iron or aluminum.

The mechanism of phosphate fixation by iron or aluminum can be represented by the following equilibrium equation:



Hydrous oxides of aluminum and iron are effective in combining chemically with  $\text{H}_2\text{PO}_4^-$  at low pH values because the stability of basic metal phosphate is greater than the hydrous oxide at the lower pH.

Processes by which the pH of the soil is increased shift the equilibrium toward a greater stability of the hydrous oxide and the release of phosphate.

Fluoride and arsenate will replace chemically combined phosphate. The effectiveness of replacement depends upon the relative stability of the compounds formed and on the concentration of the replacing anion. Phosphate is several

times as effective in replacing arsenate and fluoride from aluminum as these anions are in replacing phosphate, except where the ratio of fluoride to aluminum exceeds six

Several organic anions were effective in preventing phosphate from combining chemically with aluminum and iron or in replacing the chemically combined phosphate. Only those anions which form stable complexes with the iron and aluminum were effective. Aliphatic hydroxyorganic acids and aromatic hydroxyacids were effective. A lyotropic series of these organic acids is presented.

Humus and lignin were effective in replacing phosphate from the basic iron phosphates, probably because of the formation of stable compounds or complexes between the active iron and humus or lignin.

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# OBSERVATIONS ON THE MEASUREMENT OF HYDROGEN-ION CONCENTRATION IN SOILS

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Three methods have been used for measuring the pH values of soils, namely, the colorimetric method using indicators and the electrometric methods using the quinhydrone electrode and the glass electrode. The first has long been discarded for accurate work, and the limitations of the second are becoming generally recognised, although a large number of values are still determined by this system. This paper reports certain observations made in using the quinhydrone and the glass electrodes and discusses their significance in terms of the theoretical basis of the electrode operation.

As it is not intended at this time to relate to particular ecological types the pH values recorded, the soil samples used, with the exception of 1, 2, and 3, were taken from samples that had been brought in at an earlier date for microbiological investigation rather than collected freshly. Samples 1, 2, and 3 were examined within 3 hours of collection. Samples 1, 2, 3, 101, 113, and 116 were all from soils at altitudes of 250–500 m, bearing vegetation associated with the “mor” and “mull” soil types, 104 and 105 were from rough pastures in limestone districts, and 120 was the humus accumulation above a limestone rock where *Calluna vulgaris* and *Agrostis tenuis* are associated. All the samples were collected either in northern England or in southern Scotland.

## METHOD

Each sample was broken up and thoroughly mixed before the experimental quantities of 5 gm were removed. Each 5-gm. sample was mixed with 10 ml of distilled water. Subsequently this mixture was diluted with a further 40 ml and thereafter with two 50-ml additions of distilled water to a total volume of 150 ml. Normal sodium chloride was added to liberate the H ions attached to the insoluble complexes. Finally oxidation was carried out with hydrogen peroxide. The pH values with both types of electrodes covering this series of dilutions and oxidations are recorded in table 1 together with the dry weights and ash contents calculated as percentages of the fresh weights of the samples. In all measurements a saturated KCl agar bridge was used, since a liquid junction led to a potential drift due to base exchange with the soil. With the quinhydrone electrode care was taken to maintain an adequate excess of the quinhydrone at all stages of dilution and oxidation.

The quinhydrone electrode pH values were calculated from the following

<sup>1</sup> The author takes pleasure in acknowledging the value of W. H. Pearsall's criticism during the preparation of this note. His thanks are also due to H. A. Krebs and R. Davies for use of the glass electrode and to his personal assistant, Miss Joan Willoughby, for her careful work.

formula,  $pH = 7.80 - E_A/58$  where  $E_A$  is the potential difference between the quinhydrone electrode and the calomel half-cell (saturated KCl).<sup>2</sup> The glass

TABLE 1  
*Comparison of pH values of soils at various stages of dilution and oxidation as determined with glass and quinhydrone electrodes*

1	2	3	4	5	6	7	8	9	10	11	12
ELECTRODE	SAMPLE NUMBER	DRY WEIGHT*	ASH*	pH VALUES OF 3-ml. SAMPLES MIXED WITH STATED VOLUMES OF DISTILLED WATER AND SUBSEQUENTLY WITH <i>N</i> NaCl AND WITH H <sub>2</sub> O <sub>2</sub>							
				Distilled water				NaCl		H <sub>2</sub> O <sub>2</sub> - 3%	
				10 ml.	50 ml.	100 ml.	150 ml.	5 ml.	10 ml.	5 ml.	15 ml.
Glass Q-H†	101	41.0	27.5	3.92 3.72	3.62 3.98	4.00 4.06	4.26 4.16	3.66 3.55	3.54 3.46	3.48 3.40	3.50 3.33
Glass Q-H	104	49.5	37.3	7.28 8.07	7.40 7.94	7.44 7.91	7.40 7.87	7.10 7.73	7.02 7.66	6.99 7.60	7.06 6.90
Glass Q-H	105	60.0	55.4	8.44 8.18	8.98 8.28	9.16 8.22	9.26 8.25	9.14 8.14	9.11 8.14	9.00 8.11	8.82 7.46
Glass Q-H	113	33.2	21.0	4.14 4.63	4.48 4.65	4.83 4.80	4.86 4.87	4.10 4.39	3.99 4.11	4.00 4.05	4.00 3.66
Glass Q-H	116	18.9	2.32	3.74 4.35	4.18 4.26	4.40 4.44	4.55 4.56	4.00 4.01	3.94 3.94	3.95 3.91	3.95 3.63
Glass Q-H	120	65.3	37.4	5.41 5.76	5.68 5.94	5.80 5.94	5.94 5.94	5.72 5.89	5.62 5.74	5.69 5.66	5.72 5.42
Glass Q-H	1	63.4	44.9	3.66 3.01	3.32 3.39	3.58 3.48	3.74 3.85	3.48 3.38	3.40 3.38	3.43 3.26	3.42 3.25
										H <sub>2</sub> O <sub>2</sub> - 30%	
										1 ml.	1 ml.
Glass Q-H	2	50.5	15.7	3.42 3.26	3.62 3.66	3.92 3.86	4.08 3.98	3.61 3.69	3.55 3.64	3.52 2.62	3.48 2.62
Glass Q-H	3	25.5	10.2	4.18 3.55	4.26 3.94	4.43 4.00	4.62 4.13	4.21 4.03	4.11 3.93	3.95 2.70	3.84 2.68

\* Dry weight determined by drying the samples for 6 hours at 105°C, ash contents by incineration in an electric oven at about 500°C  
† Q-H = quinhydrone.

electrode pH values were obtained from the direct-reading scale of the potentiometer after calibration with standard buffer solutions.  
<sup>2</sup> Pearsall, W. H. The soil complex in relation to plant communities. *Jour. Ecol.* 26: 180, 1938.

The data in table 1 form the basis for the subsequent discussion. The dilution effects follow the expected pattern and the upper limit for the quinhydrone electrode is shown very clearly with sample 105. Two points are worthy of special mention: first, the difference that exists between the pH values as recorded by the two electrodes with each sample at the initial dilution and in many cases throughout the latter operations, and second, the effect of oxidation with  $H_2O_2$ . The oxidation produced a marked decrease in the pH value as measured with the quinhydrone electrode, whereas with the glass electrode the changes are very much smaller and are variable in direction.

#### DISCUSSION

Consideration of the mechanism of the glass and quinhydrone electrodes shows that whereas the potential of the first is directly proportional to the pH difference across the membrane, in the second the potential-pH equation<sup>1</sup> contains a term involving the quinone/hydroquinone ratio

$$E_A = E_o - \frac{RT}{2F} \ln \frac{[S_2]}{[S_o]} + \frac{RT}{2F} \ln [K_1 K_2 + K_1 [H^+] + [H^+]^2] \quad (1)$$

Any redox system which changed the ratio  $\frac{[S_2]}{[S_o]}$ , such as hydroquinone/quinone, would bring about a change in the potential of the system that could be misinterpreted as a change in the hydrogen-ion concentration. It is clear that  $E_A$  can be varied either by changing the concentration of the oxidant  $[S_o]$  or that of the reductant  $[S_2]$  or by varying the concentration of the hydrogen ion  $[H^+]$ . If, therefore, the quinhydrone system is to be used for measuring pH values, the ratio  $\frac{[S_2]}{[S_o]}$  must be kept constant and  $[H^+]$  must be large in relation to  $K_1$  and  $K_2$ , which are the dissociation constants related to the following equations

$$K_1 = \frac{[H^+][H \text{ Red}^-]}{[H_2 \text{ Red}]} \quad K_2 = \frac{[H^+][H \text{ Red}^{--}]}{[H \text{ Red}^-]} \quad (2)$$

These two conditions are fulfilled in practice by using the electrode in solutions of  $< \text{pH } 8$  and avoiding measurements in solutions containing active redox systems. Although in soil measurements the upper limit of pH has been recognised, the inaccuracies that result from use of the electrode in suspensions containing active redox systems have not, in general, been recognised except in the limited sense that the electrode is not suitable for use in the presence of manganese. The term "active redox system" takes into account the fact that not all biological systems may react with the quinhydrone but some may be "sluggish" in the sense used by Barron.<sup>4</sup> The redox systems may be not biological but purely organic compounds, such as lignin derivatives and polyphenol compounds, resulting from microbiological metabolism.

<sup>1</sup> Clark, W. M. *The Determination of Hydrogen Ions*, p. 383, equation 32. London, 1928.

<sup>4</sup> Barron, E. S. G. *Cellular oxidation systems*. *Physiol Rev* 19: 184, 1939.

From equation (1) it may be deduced that at any one pH value the presence of a redox system of such a potential that the HQ/Q ratio becomes  $<1$  will increase the  $E_h$  value measured and lead to calculation of a pH value lower than that which actually exists in the solution. This deduction is substantiated by consideration of the pH values recorded in table 1. Comparison of the figures in columns 10 and 12 shows that following oxidation with  $H_2O_2$  the real change of the pH value as recorded by the glass electrode is small and variable in sign, whereas the change recorded by the quinhydrone electrode is always very much larger—in sample 113, 45 times as large—and always of the same sign, namely, in the direction indicating increased acidity.

These observations may be applied to explain the differences revealed in table 1, column 5, between the pH values recorded by the glass and quinhydrone electrodes. On this basis, 101, 105, 1, 2, and 3 are soils with redox potentials sufficient to lower the HQ/Q ratio, whereas 104, 113, 116, and 120 have potentials which increase the ratio. Although the ecological character of the soils does not permit classification of the first group as oxidizing and of the second as reducing, it should be remembered that the potentials of the soils as measured in the laboratory are no guide to the activity of the effective redox systems, which may be due in part to microbiological activity and in part to the chemical constitution of the partly decomposed plant remains, in particular to the polyphenol type of compound and its oxidation products which arise from the lignin complex. Though it is reasonable to suggest that the differences between the pH values recorded by the two electrodes can be explained on the basis of the influence of the redox systems in the soils upon the HQ/Q ratio, it is not as yet possible to define, even in general terms, the nature of the active redox systems that are responsible.

The effect of dilution upon the recorded pH values is complex. The glass electrode pH values in table 1 suggest that the dilution effects on the pH values of the moderately strong acids in the soils (revealed by the titration curves) are subject to considerable buffer action from weak acids, bases, and their salts. In most cases the effect of dilution from 100 ml. to 150 ml. is closer to the calculated value for an unbuffered strong acid than at other dilutions. This is to be expected, since the content of water-soluble weak acids, bases, and their salts is limited and, once completely leached out of the insoluble complex, further dilution does not alter the [salt]/[acid] ratio on which the action depends. The values recorded for samples 101 and 1 at the 50-ml. dilution, compared with those at the 10-ml. dilution, suggest a complex relationship between the substances soluble at the two dilutions.

Dilution results in pH changes with the quinhydrone electrode in the same direction as with the glass electrode except in the first dilution stages of samples 101 and 1, where increases are recorded. At the final volume of 150 ml., the pH values by both electrodes are virtually identical in 113, 116, and 120, close together in others, and only substantially different in 104, 105, and 3. The differences between the dilution effects upon the two electrodes can be explained along the following lines. The HQ/Q ratio in the 10-ml. dilution will be determined by

the amount as well as by the potential of the active redox systems of the soil. The degree to which the ratio varies from 1 will determine the difference between the pH values recorded by the two electrodes. On dilution, more quinhydrone will pass into solution, and only if the amount of the active redox system in the soil is large enough to maintain the HQ/Q ratio at the value established in the 10-ml dilution will the real effect of dilution upon the pH value be recorded by the quinhydrone electrode. Where the amount of the redox system is insufficient to maintain the HQ/Q ratio, the change in the pH recorded on dilution will be a combination of two effects: the dilution affecting the real pH of the solution, and a variation in the  $\frac{[S_+]}{[S_-]}$  ratio of equation (1) which, bringing about a change in  $E_A$ , will be calculated as a change in pH. As dilution is increased, more quinhydrone will pass into solution, and since the amount of the redox systems in the soil is limited, the ratio  $\frac{[S_+]}{[S_-]}$  must tend to approach unity. Under this condition, the values recorded by the two electrodes will tend to approach one another. In those soils in which there is a difference between the pH values recorded by the two electrodes at the 150-ml dilution, the amount of the active redox system is large enough to maintain the HQ/Q ratio at a value not equal to 1.

#### SUMMARY

Substantial differences were observed between the pH values recorded by the quinhydrone and glass electrodes for a number of soils under similar experimental conditions. An explanation has been provided by considering the effect of the redox systems in the soils on the HQ/Q ratio in the quinhydrone system. Maintenance of this ratio at a constant value, customarily unity, is essential if the values recorded with the quinhydrone electrode are to be correct measurements of the pH of the soil. The pH of any soil containing a redox system that disturbs this ratio cannot be determined accurately by this system.





## SOME TESTS OF THE DIFFUSION THEORY, AND LAWS OF CAPILLARY FLOW, IN SOILS<sup>1</sup>

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Diffusion theory has been applied to the capillary movement of water in soil by Gardner and Widtsoe (8), Childs (4, 5), Nicholson and Childs (12), and Ostashev (13). In this theory it is assumed that the capillary flow of moisture is a phenomenon analogous to heat transmission in solids or to molecular diffusion in gases. In testing the diffusion theory, the authors have repeated and amplified some of the tests used by Ostashev. The authors' own data as well as those of others are utilized in this paper, in which certain simple laws of the movement of soil moisture become evident.

Tests of the validity of the diffusion theory seem pertinent because it is known, as shown by Christensen (6) and others, that in the basic equation of capillary flow of Buckingham (1),  $v = -k\partial\psi/\partial x$ , the capillary conductivity coefficient  $k$  is not a constant, but varies rapidly with the capillary potential, and hence with the moisture content, making the equation and equations derived from it untractable, an easier approach being desirable. In the above equation,  $v$  is the quantity of water conducted per unit time across unit area normal to the  $x$  direction,  $\psi$  is the capillary potential, and  $\partial\psi/\partial x$  is the rate of change of  $\psi$  in the  $x$  direction.

Gardner's derivation of the diffusion equation was based on the action of capillary forces in the soil. He assumed, lacking other information, that the quantity  $k$  in Buckingham's equation was a constant, independent of the moisture content. He later modified this viewpoint (9). Childs derived the diffusion equation on quite another basis, ignoring both the forces and the quantity  $k$ , as defined above. Ostashev did not explicitly derive the differential equation of diffusion theory. He used one of its solutions in some soil tests, the results of which he interpreted as establishing the theory.

### THEORETICAL FORMULA

The basic equation assumed by Childs (4) is

$$\partial Q/\partial t = -k\partial c/\partial x \quad (1)$$

where  $\partial Q/\partial t$  = mass of capillary water flowing across unit area perpendicular to the  $x$  direction in unit time,  $c$  = ratio of mass of water to mass of dry matter,  $\partial c/\partial x$  = moisture gradient, and  $k$  = diffusion coefficient.

From equation (1) and the equation of continuity, Childs showed that for one-

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dimensional flow,

$$\partial c / \partial t = (k/\sigma) \partial^2 c / \partial x^2 \quad (2)$$

in which  $\sigma$  = mass of dry matter in unit volume of soil (bulk density)

The solution of equation (2), studied by Ostashev, is for the case in which a constant moisture percentage is applied and maintained to one end of an initially air-dry, horizontal column of soil. The solution to this problem, if the diffusion theory is applicable, is (in somewhat rearranged form and with different notation from that used by Ostashev)

$$c - c_i = (c_s - c_i) \left[ 1 - (2/\sqrt{\pi}) \int_0^{x/2\sqrt{(k/\sigma)t}} e^{-\beta^2} d\beta \right] \quad (3)$$

where  $c$  = moisture percentage at any point distance  $x$  from the source of moisture and at time  $t$  after application of the moisture,  $c_i$  = initial moisture percentage, taken constant, throughout the column (air-dry moisture percentage),  $c_s$  = moisture percentage applied and maintained at all time after  $t = 0$  at the wetted end ( $x = 0$ ) of the soil column,  $\beta$  = variable of integration which vanishes in the evaluation of the definite integral

Since the above solution stems from the analogous heat flow problem, it is of interest to remark that equation (3) applies in the latter case to the problem in which a constant temperature  $c_s$  is suddenly applied to, and maintained at, one end of a long bar of metal, initially at temperature  $c_i$  throughout, the bar having thermal diffusivity  $(k/\sigma)$  and being coated with a nonconducting material except at the heated end. In treatises on heat flow, equation (3) is usually derived with  $c_i = 0$  and  $c_s = 1$  [cf Carslaw (2, p 35) and Schack (16, p 35)]

The mass of water  $Q$  entering unit cross section of the soil tube in the time interval  $t = 0$  to  $t = t$  is, referring to equation (1),

$$Q = k \int_0^t (\partial c / \partial x) dt \quad (4)$$

where  $\partial c / \partial x$  is evaluated at  $x = 0$

With the aid of equation (3), equation (4) yields

$$Q = 2(k\sigma/\pi)^{1/2}(c_s - c_i)t^{1/2} \quad (5)$$

that is,

$$Q = At^{1/2} \quad (6)$$

where

$$A = 2(k\sigma/\pi)^{1/2}(c_s - c_i)$$

If  $c$  is a constant in equation (3), the upper limit of the integral must be constant, that is,

$$x = Bt^{1/2} \quad (7)$$

where  $B$  is a constant depending on  $(k/\sigma)$  and the constant value of  $c$

## TESTS OF THE THEORY

Ostashev found equations (6) and (7) to be verified where  $x$  and  $t$  were values of distance of advance and time of advance of the wet-dry interface. The first tests, made to check Ostashev's results, consisted of connecting glass tubes, about 150 cm. long and 0.75 cm. inside diameter, filled with soil, in series with tubes of about the same length and 0.475 cm. inside diameter, filled with water, and observing the position of the wet-dry front in the soil tubes and the air-water front in the water tubes at a number of times after putting the water and soil in contact. Both tubes were maintained horizontal, the water tube at a level 1 cm. lower than the soil tube, to assure absence of gravitational head. Tubes larger than about 0.5 cm. inside diameter cannot be used for water tubes, since surface tension will then not maintain a vertical meniscus.

The soil samples used were Glencoe silty clay loam, Ida silt loam, Fayette silt loam, Monona silt loam, and a washed quartz sand. The Glencoe is a slightly permeable prairie soil found in depressed areas, the Ida a highly permeable upland soil, the Fayette a forest soil of moderate permeability, the Monona a prairie soil of moderate to high permeability. The samples were air-dried aggregates which would pass through screens of 1-mm. openings and be retained on screens of 0.5-mm. openings. Each soil tube, during filling, was held in a vertical position and tapped, care being taken to have the packing uniform for all samples.

Figure 1 shows experimental results for three tubes of the Glencoe, two tubes of the Ida, and two tubes of sand. Data are not graphed for the full length of tubes because during the run some nearby vibration equipment used in connection with other work was inadvertently set in operation, causing the rate of moisture movement to increase.

The tests were repeated, this time with the Glencoe, Fayette, and Monona soils and the sand. Figure 2 shows the results, each curve being the average of two runs. The movement in the Glencoe soil in figure 2 is faster than in figure 1. This may be because the Glencoe samples in figure 1 were taken at a 10-15-inch depth, where, for this soil, there is less clay than in the 0-6-inch depth, from which the samples for the tests of figure 2, and subsequent use, were obtained.

Not only clay content, but also degree of soil packing affects the rate of water movement. Sreenivason (17) has presented some data on this matter for Poona and Bangalore soils. A cross-plot of part of his figure 1 (fig. 3) shows the effect of packing in the Poona soil, and at the same time serves as further verification of equation (7). Similar results, not shown here, were obtained for the Bangalore soil. In figure 3, 0, 50, 80, and 100 per cent packing correspond to air-dry volume weights of 1.143, 1.236, 1.300 and 1.346 gm./ml. The samples consisted of all the dry matter that would pass through a 0.5-mm. screen. Further details with regard to the manner of packing are given by Ramdas and Mallik (15, p. 3). Plots of  $B$  [equation (7)] vs. decrease in volume due to packing, as recorded by Sreenivason, yielded straight lines for both the Poona and Bangalore soils.

Other data available for testing equations (6) and (7) are those of Green and Ampt (10), Gardner (7), and Gardner and Widtsoe (8). Gardner was concerned with the measurement of a certain capillary transmission constant. He observed

the rate of intake of water and the horizontal movement of a wetted soil front in a layer of soil in the form of a section of an annulus of a circle. Various sizes of sectors were used. In one case the inner radius was infinite, from which it is to be inferred that the outer radius was also infinite and that the flow was therefore rectilinear. The results of this case are given in figure 4, where the square root of time is used as abscissa.

In Gardner and Widtsoe's figure 6, the distance of advance of a wet front is plotted against time for soil in a rectangular box, 6 by 9 cm. in cross section

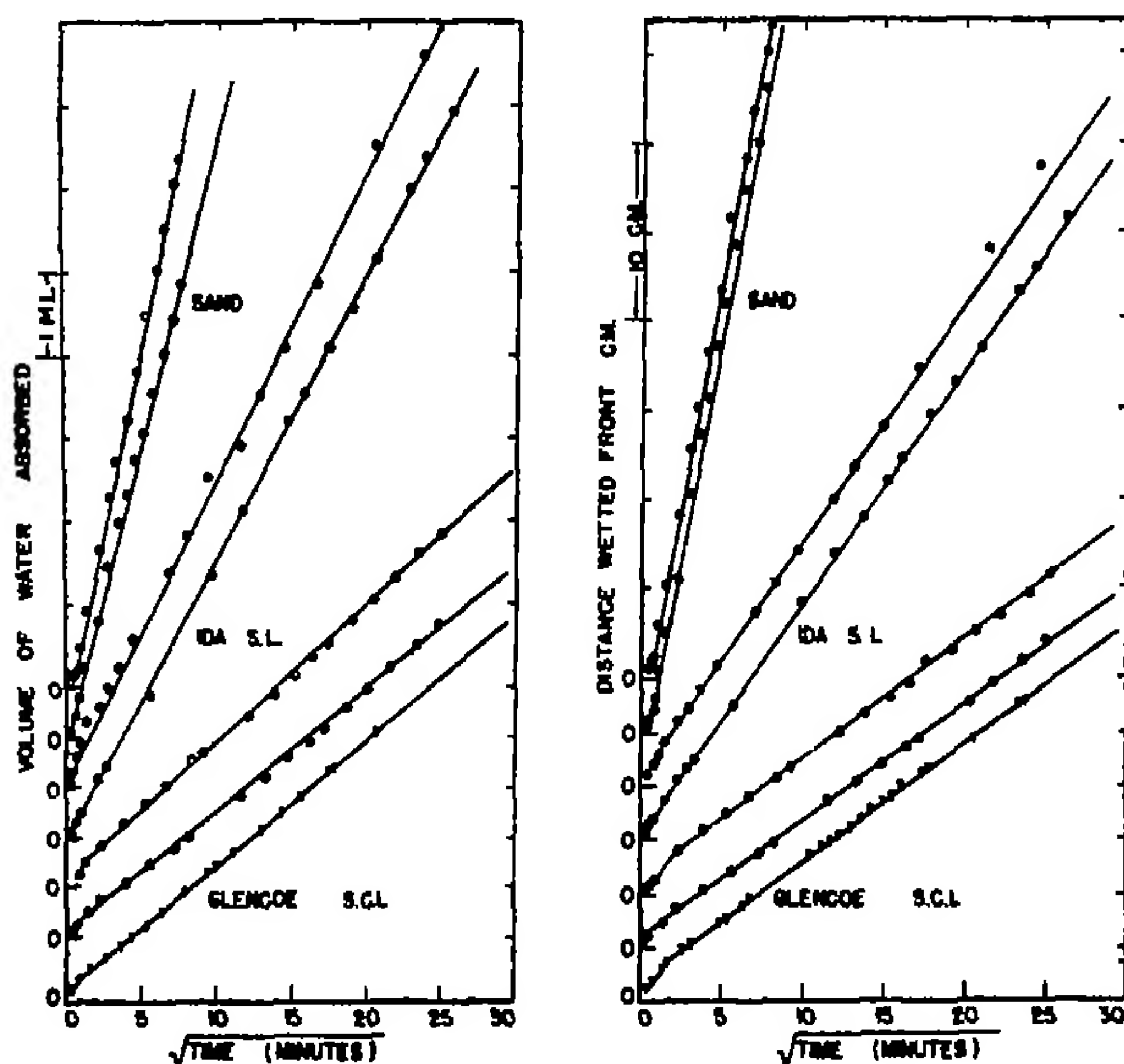


FIG 1 CAPILLARY MOVEMENT OF WATER, INTO HORIZONTAL COLUMNS OF GLENCOE SILTY CLAY LOAM, IDA SILT LOAM, AND SAND, FROM A SOURCE OF FREE WATER

Origin for each curve indicated by 0

One end of the box was bent downward and kept permanently in contact with water maintained at a constant height, about 10 cm. below the center of the box. In figure 5 the experimental points are plotted against the square root of time. On this same figure, Green and Ampt's data taken from their table 3 are presented in the same way. The experimental points are seen to fall on a straight line. This is particularly of interest, because these data, as originally presented, were used to discredit the square root of time law given by equation (7). The reason for the good fit in figure 5 is that the straight line drawn through the experimental points is not forced through the origin of coordinates because

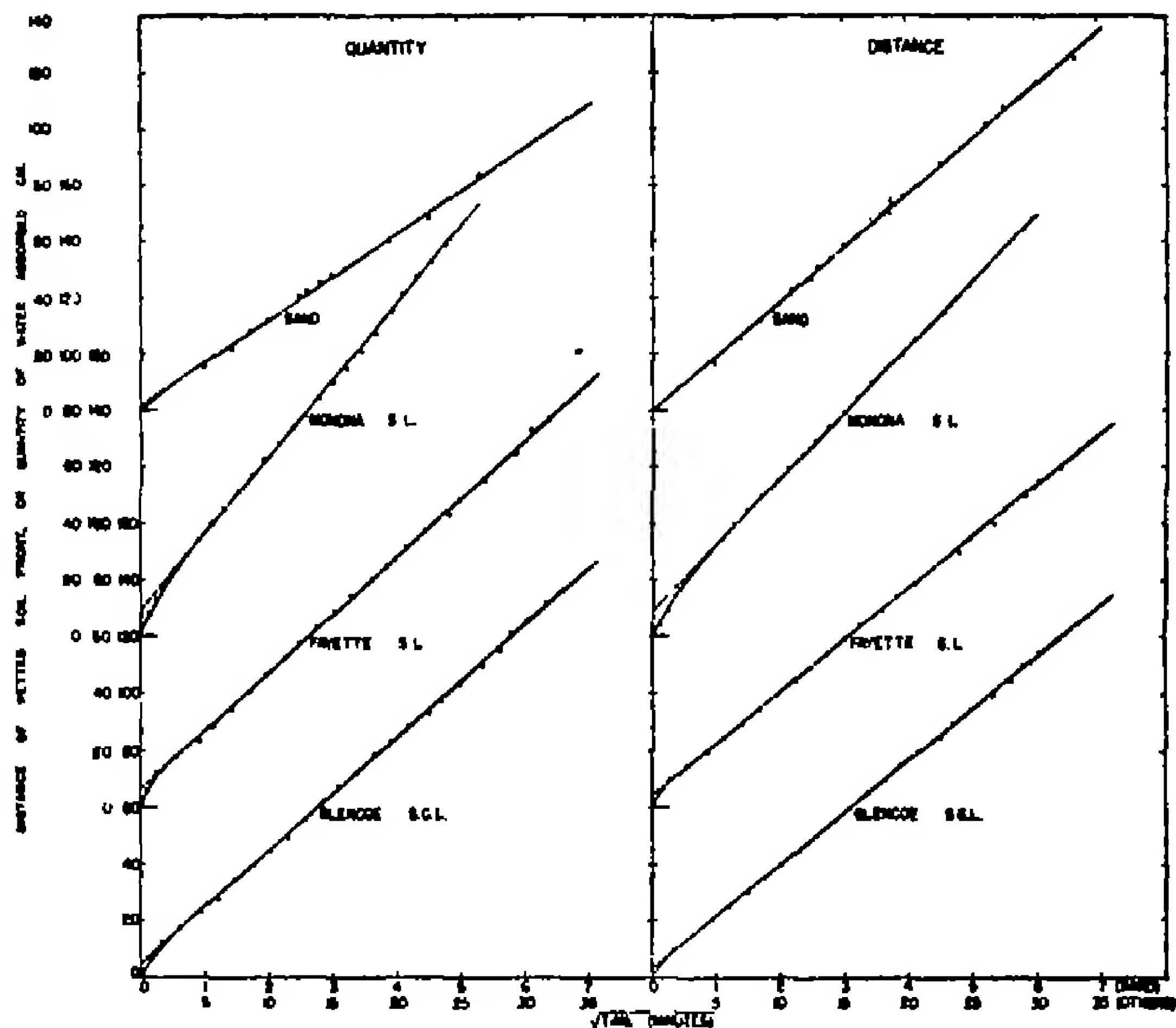


FIG 2 CAPILLARY MOVEMENT OF WATER, INTO HORIZONTAL COLUMNS OF GLENCOE SILTY CLAY LOAM, FAYETTE SILT LOAM, MONONA SILT LOAM, AND SAND, FROM A SOURCE OF FREE WATER

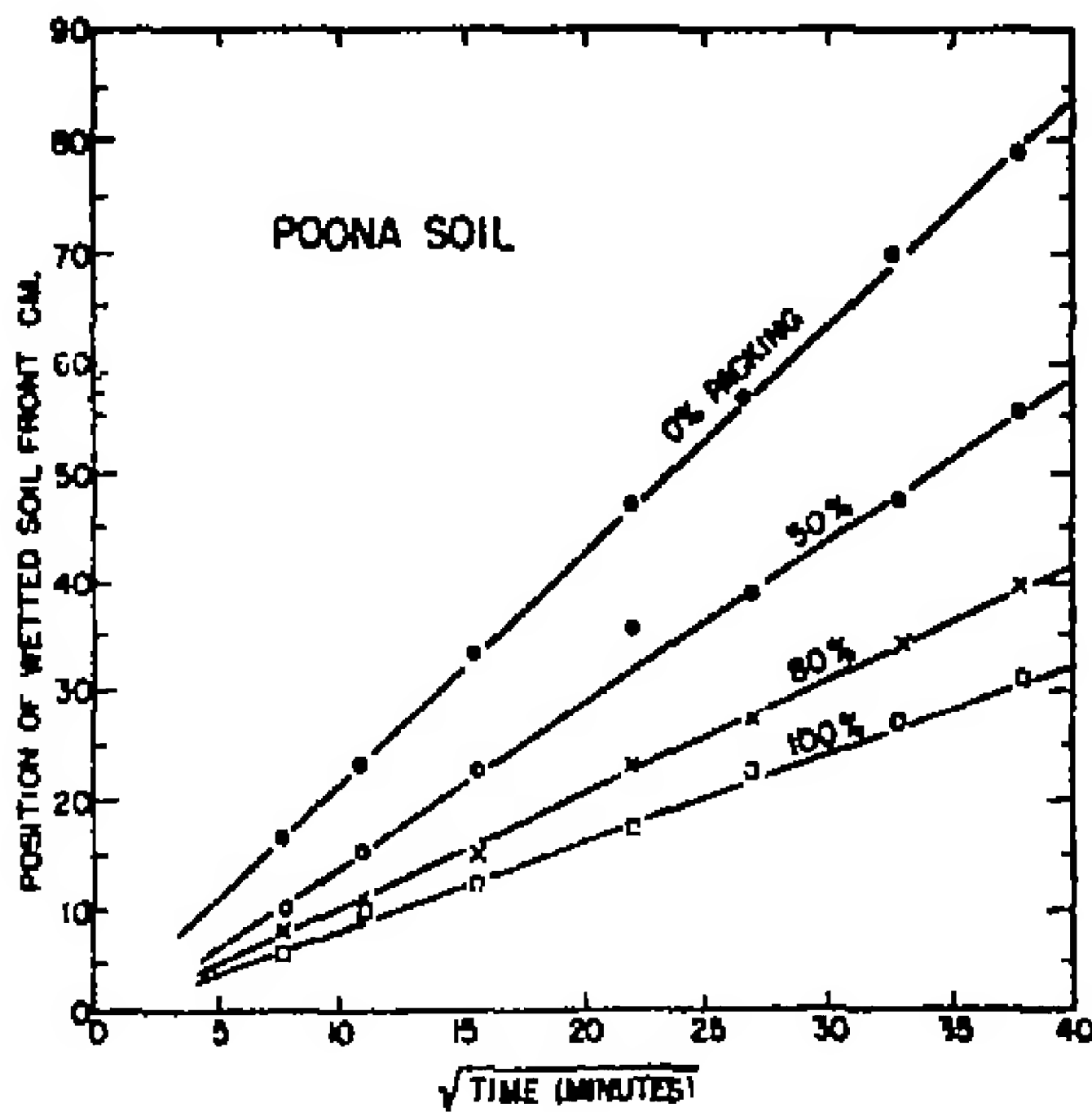


FIG 3 CAPILLARY MOVEMENT OF WATER INTO HORIZONTAL SOIL COLUMNS FROM A SOURCE OF FREE WATER  
Data of Sreenivasan (17)

mertial forces may be important during the initial movement of free water into dry soil.

Green and Ampt in their table 3 also give data on water absorbed in horizontal soil tubes. The quantity absorbed was found to be strictly proportional to the square root of time.

In all the curves, figures 1 to 5, except for small deviations near the origin, where, as just mentioned, inertial forces may be large in comparison with the capillary forces acting in the soil-water, equations (6) and (7) seem verified. It might appear, therefore, that the diffusion theory is well justified. But this is not necessarily true. In the first place, equations (6) and (7), if the constants  $A$  and  $B$  are given different meanings, can be derived on the capillary tube hypothe-

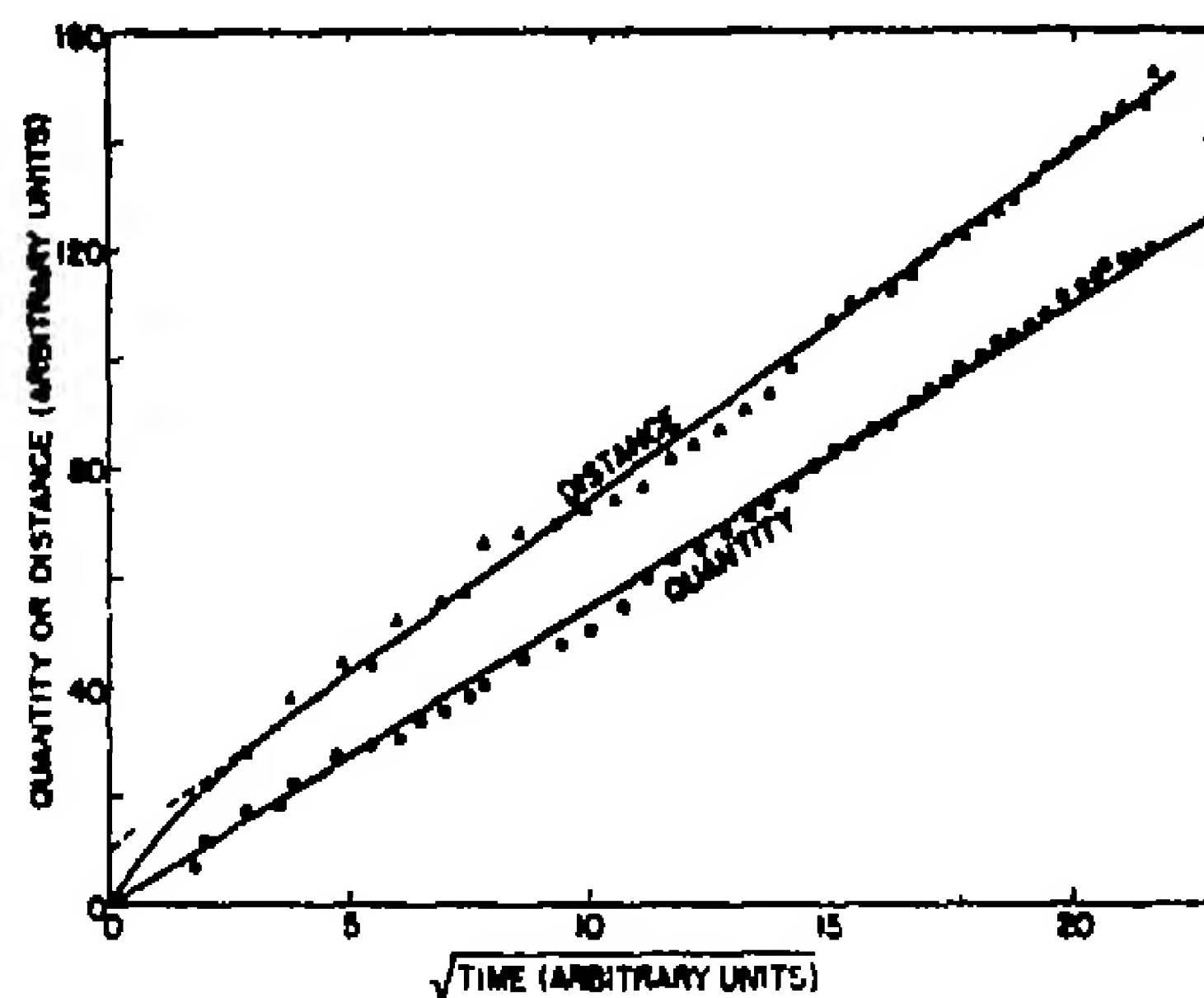


FIG. 4. CAPILLARY MOVEMENT OF WATER INTO A HORIZONTAL SOIL COLUMN FROM A SOURCE OF FREE WATER.

Data of Gardner (7, fig. 6)

sis, as described, for example, by Keen (11, p. 94). In the second place, Ostashev's statement, that, at the border between wet and dry soil, "the moisture of the soil can be taken as constant, in relation to the constancy of its initial moistness (air-dry condition)" is not generally recognised as true;<sup>3</sup> and if the statement is true, it is not a criterion for the diffusion theory, because this theory does not provide for an abrupt front, as found in the foregoing experiments.<sup>4</sup>

To obtain experimental data pertinent to these points, further tests were made. The method was similar to that for figures 1 and 2, except that, after the water

<sup>3</sup> Gardner's figure 4A (7) indicates that Ostashev's statement is correct, but Gardner comments that the apparently constant difference in moisture percentage at the wet-dry front will decrease with time.

<sup>4</sup> Observations with a microscope emphasize, even more than is perceptible to the naked eye, the reality of the sharp boundary between the wet and dry soil.

had penetrated into the soil a certain distance, the moisture distribution in the soil column was determined. The lengths of penetration used were 10, 20, 30, etc., up to 120 cm. The measurements were made by weighing successive 10-cm. sections of the wetted soil, each section being isolated by breaking rapidly the glass tube with contents into the section after the water had penetrated the desired distance. Moisture percentages were referred to the oven-dry weight of the soil (105°C)

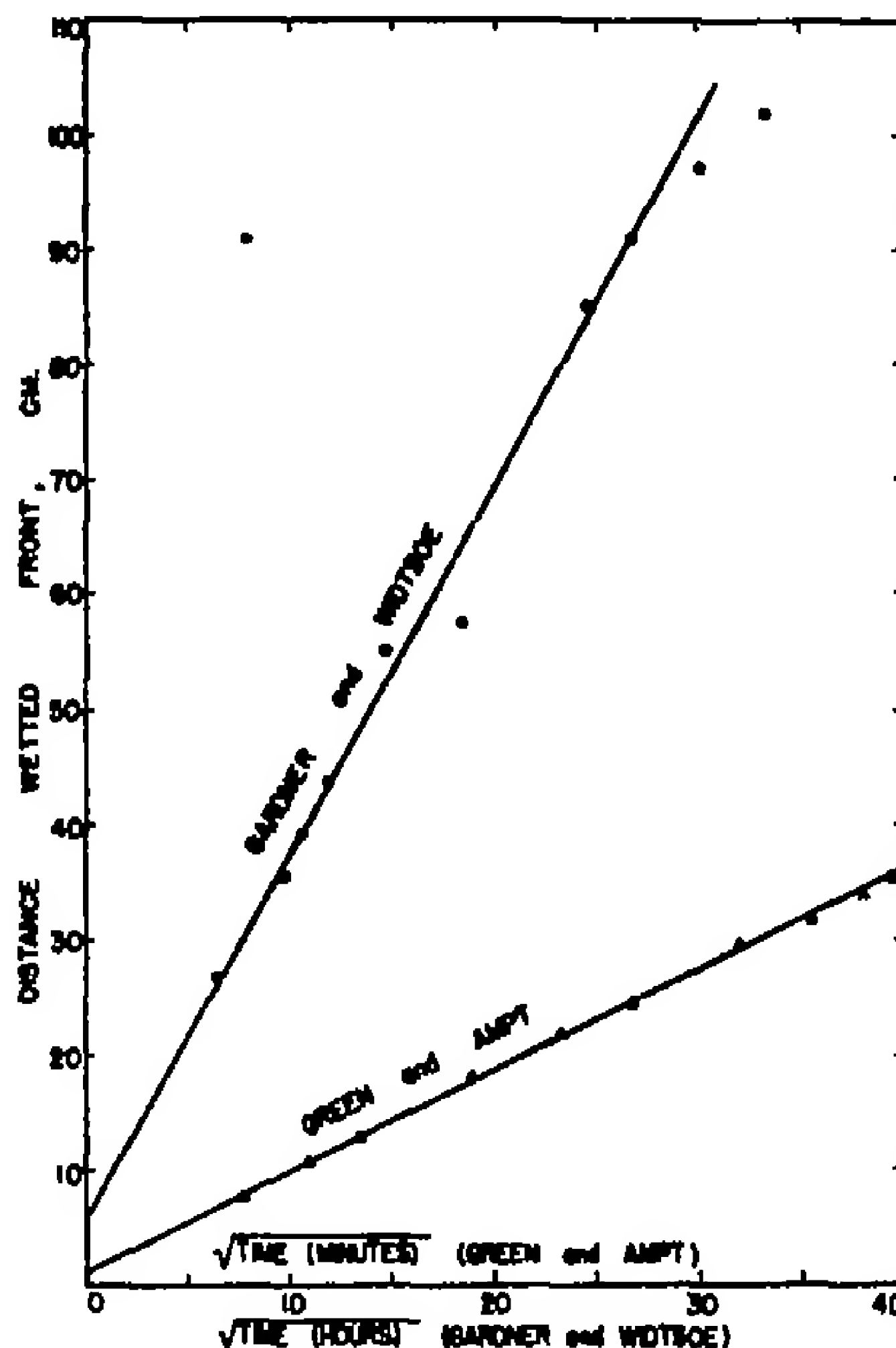


FIG 5 CAPILLARY MOVEMENT OF WATER INTO HORIZONTAL SOIL COLUMNS FROM A SOURCE OF FREE WATER

Data of Gardner and WidtsOE (8) and of Green and Ampt (10)

Figure 6 shows the moisture distribution for the Fayette, Glencoe, and Monona soils. For the sand, the moisture percentage did not vary with distance. Each curve is the average of two trials. The experimental points are located at 5, 15, 25, 35, etc. cm. from the origin, since these are the average distances, from the source of free water, of the soil sections in question. The ordinates of the curves, except in two or three cases, decrease with distance from the free water, the moisture percentage in the soil adjacent to the free water being generally about 65 per cent for the Fayette and Monona soils and about 55 per cent for the Glencoe.

The reference level for a particular curve is indicated by a horizontal line and arrow. The reference level is 60 per cent in all cases for the Fayette and Monona, and 50 per cent, except except for the 10-cm. and 20-cm. long samples, for the Glencoe. The curve for the 90-cm. sample of Monona soil was inadvertently omitted from figure 6.

In figure 7 the experimentally obtained moisture distributions for the 40-, 80-, and 120-cm. long samples of the Fayette and Monona soil are replotted, together with corresponding theoretical curves. The experimental curves are shifted up or down slightly, so that 65 per cent is the moisture percentage at  $x = 0$  in each case. Included in the experimental data are 5 per cent moisture

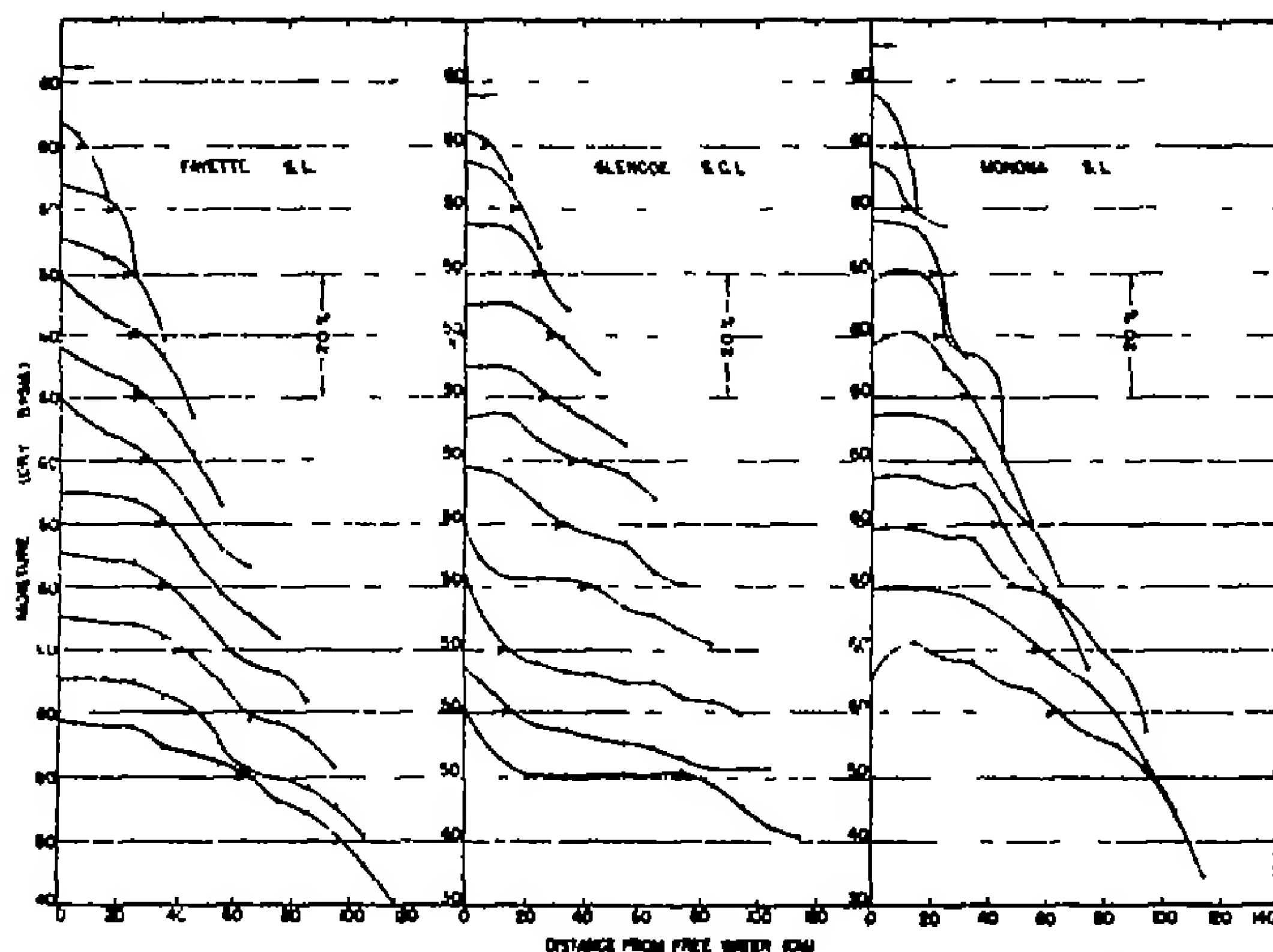


FIG. 6. MOISTURE DISTRIBUTION IN HORIZONTAL SOIL COLUMNS AFTER WATER HAS ADVANCED 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, AND 120 CM

percentages, which are approximately the air-dry values just ahead of the wet front.

The theoretical curves in figure 7 are plots of  $c$  against  $x$ , as given by equation (3). The numerical values used are as follows:  $c_s$  is taken at 65 per cent and  $c_i$ , the air-dry condition, at 5 per cent, the values of  $t$  are read from figure 2, and are those indicated in figure 7, the bulk density  $\sigma$ , about the same for each sample, is taken at 0.9 gm./ml., the quantity  $(k/\sigma)$  is obtained with the aid of equation (5), using values of  $Q$  read from figure 7 at the appropriate values of  $t$ . The value of  $(k/\sigma)$  for the Fayette is found to be 50 [gm./cm. minute]/(gm./cm.<sup>3</sup>) = 50 cm.<sup>2</sup>/minute, and for the Monona soil approximately 100 cm.<sup>2</sup>/minute.<sup>4</sup>

<sup>4</sup> A numerical example for the sample of Fayette soil 80 cm. long will illustrate the procedure. At the right of figure 2, 80 cm. on the Fayette curves corresponds to  $t^{1/2} = 20.8$  minutes<sup>1/2</sup>. Therefore  $t = 430$ . At the left of figure 2,  $t^{1/2} = 20.8$ , corresponds to



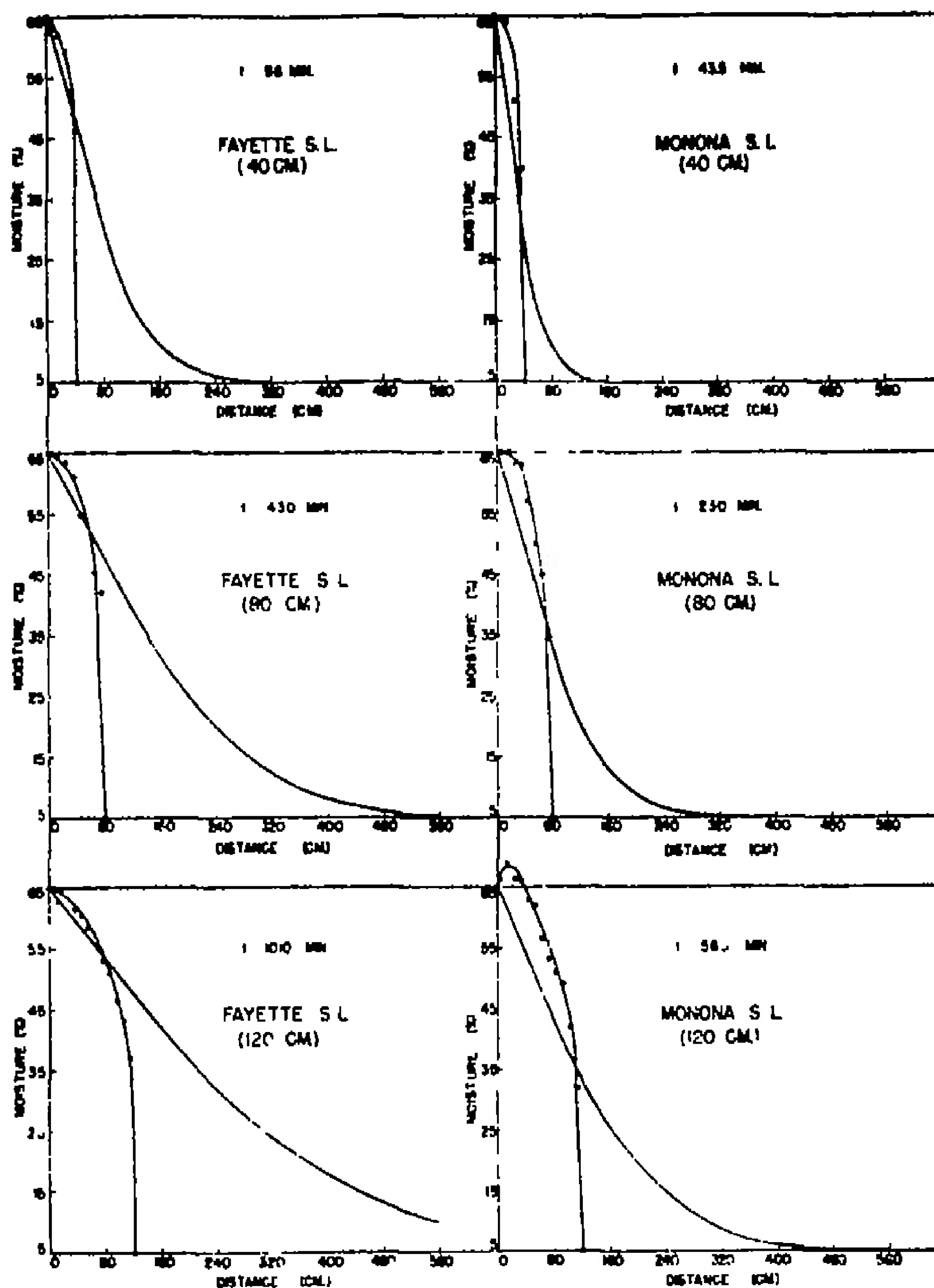


FIG 7 COMPARISON OF EXPERIMENTALLY OBSERVED MOISTURE DISTRIBUTIONS (CIRCLES) WITH THEORETICAL CURVES OF DIFFUSION THEORY [Equation (5)]

Figure 7 shows, as suspected, that the observed moisture distributions do not agree with the theoretical curves. The abrupt fronts, even more abrupt than

$Q = 90 \text{ cm} = 90 \text{ cm}^3/\text{cm}^2$  By dividing equation (5) by  $\sigma$  and solving for  $(k/\sigma)^{1/2}$ , it is found that  $(k/\sigma)^{1/2} = (Q/\sigma)\tau^{1/2}/[2(c_s - c_i)t^{1/2}] = (90/0.9)(1.772)/[2 \times 0.60 \times 20.8] = 7.09$ , whence  $(k/\sigma) = (7.09)^2 = 50$ . Therefore, the upper limit of the integral in equation (5) is  $x/2[(k/\sigma)t]^{1/2} = x/2[50 \times 430]^{1/2} = x/147$ , and  $c = 0.05 + 0.60[1 - P]$ , where  $P = (2/\pi)^{1/2} \int_0^{x/147} e^{-\beta^2} d\beta$ , is the probability integral of argument  $x/147$ .  $P$  is tabulated in Peirce's tables (14, pp 116-121) and elsewhere.



those shown in the figure, are concave downward, whereas the theoretical curves are concave upward and have no sharp fronts.

The conclusion, therefore, is that the diffusion theory does not account for the movement of moisture, under capillary forces, from free water into an uncompressed air-dry soil.<sup>6</sup> Furthermore, the law  $x = Bt^{1/2}$  disproves, rather than proves, the diffusion theory. This law, known in diffusion theory as the "law of times" (3, p. 42), requires that if the moisture percentage is (say) 50 per cent at time  $t$ , where  $x = x_1$  then the 50 per cent moisture will be observed at the point  $x_2$  at a time  $t_2$  in accordance with the relation  $x_1/t_1^{1/2} = x_2/t_2^{1/2}$ . The latter condition can be true only if the successive moisture distributions are of the theoretical forms shown in figure 7. The time law obviously cannot hold for the experimental moisture distributions, since these distributions do not resemble the theoretical curves.

#### LAWS OF MOISTURE MOVEMENT

Although the diffusion theory could not be verified, the data and those of other investigators show that free water is imbibed, under capillary forces, into uniform, drier soil, in accordance with the law

$$Q = At^{1/2} + a \quad (8)$$

and that the movement of the wetted front follows the law

$$x = Bt^{1/2} + b \quad (9)$$

These equations are the same as equations (6) and (7), except that small constants  $a$  and  $b$  have been added to account for the presumed action of the inertial forces, or of other effects in the soil water at and near  $x = 0$ . Near  $x = 0$  the laws do not hold. The failure of the above laws near  $x = 0$  and  $t = 0$  may be compared with the failure of Darcy's law for saturated ground-water flow when the velocities become too high.

The rate of advance of wetted front is obtained by differentiating equation (9) with respect to  $x$  and is

$$dx/dt = (1/2)Bt^{-1/2} \quad (10)$$

Equations (8) and (9) and (10) will not be valid for all values of  $x$  and  $t$ . The largest value of  $t$  for which the laws appear to hold is 730 hours (figure 5, curve of Gardner and Widtsoe), the largest values of  $x$ , 300 cm., for Khaskov sand, and 150 cm. for Dniepro loess, examples from Ostashev (13).

It appears that any complete theory of infiltration or of capillary rise in soil should reduce to equations (8) and (9), when the gravitation constant  $g$  is made 0.

<sup>6</sup> In Childs' work, where a fair agreement of experimental and theoretical results based on diffusion theory was found,  $(k/\phi)$  was of the order 1 to 20 cm<sup>2</sup>/day, heavy clay soils being considered for which several months were required for the moisture distributions to change appreciably. It is likely that in such problems a part of the water moves in the vapor stage, then it might be expected to follow diffusion theory. The type of slow moisture movement studied by Childs, except in special cases, is not of primary interest agriculturally. When moisture is below the field capacity, plant roots tend to move to water rather than water to roots.

A theoretical expression giving the soil moisture distribution in the soil columns for which equations (8) and (9) are valid awaits development. Replicated data of the type given in figure 6 are needed to check such a theory.

Since in equation (9) the constant  $b$  is small, an obvious application of the laws is that of the lateral spreading of water from furrows. Doubling the spacing of the furrows increases, by a factor 4, the time required for the wetted fronts from adjacent furrows to meet.

The laws may be important in the evaluation of soil structure, erodibility or other soil characteristics. A soil in good structure may have high values of  $A$  and  $B$ . If the method is useful in soil structure study, and undisturbed core samples are used, it will probably be easier to measure  $A$  than  $B$ , since such samples in glass would not be easy to obtain. Glass holders or the equivalent would be needed to measure  $B$ , since the advance of the wetted front must be observed. But, since  $A$  and  $B$  are directly proportional to each other (neglecting  $a$  and  $b$ ), either of these coefficients might be used as a measure of soil structure. Since  $A$  and/or  $B$  would be measured with the soil in a horizontal position, the effects of cracks and wormholes, which are disturbing in core-sample measurements, would be minimised. The constants  $A$  and  $B$  are, of course, nothing more than the slopes of the straight lines obtained by plotting  $Q$  vs  $t^{1/2}$  and  $x$  vs  $t^{1/2}$ . Obtaining the slope of the curves thus constitutes measurement of  $A$  or  $B$ .

#### SUMMARY

When water moves horizontally under capillary action into uniform air-dry soil from a source of free water, experiments show

- 1 The differential equation of diffusion theory [equation (8)] is not valid,
- 2 The quantity  $Q$  of water imbibed in time  $t$  per unit area of soil normal to the flow direction at an interface of soil and free water is

$$Q = At^{1/2} + a$$

where  $A$  and  $a$  are constants,

- 3 The distance  $x$  of advance of the wetted front is expressible by

$$x = Bt^{1/2} + b$$

where  $B$  and  $b$  are constants. The constants  $a$  and  $b$  are small. The above equations are not valid near  $t = 0$  and  $x = 0$  unless  $a$  and  $b$  are 0.

These equations may be considered as formulations of laws of capillary movement.

Values of the coefficients  $A$  and  $B$  should be closely related to the structural condition of the soil and its erodibility.

A satisfactory theory of infiltration or capillary rise of water in soil should reduce to the above laws if the gravitation constant  $g$  which of necessity will appear in them, is set equal to 0.

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# REACTIONS OF MUSCOVITE, BENTONITE, AND THEIR TREATED RESIDUES

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Kaolin, montmorillonite (bentonite), and muscovite are closely related soil minerals and are of great importance as soil constituents. Studies on the disintegration of kaolin and the chemical actions of ground or heated kaolin were recently published (8). Similar studies on muscovite and bentonite are reported in this paper.

A number of investigators have reported on the disintegration of kaolin and related soil minerals by grinding and other treatments. Johnson and Lawrence (4) found, for a series of kaolinite samples ground to several particle sizes, that the base-exchange capacity was a function of surface area. Pinkser *et al.* (9) report that kaolin is water-soluble. March (6) found several laboratory methods of disintegrating clays to yield alumina. Nutting (7) has reported that montmorillonite dissolves in slightly acid water and that in pure water silica only is dissolved. Laws and Page (5) found that dry grinding kaolin for 96 hours at first increased the size of particles, then decreased the size and increased the base-exchange capacity, which leveled off with time. Caillere and Henm (2) showed that montmorillonite when treated with certain chemicals is converted into kaolinite. Jackson and Truog (3) found that grinding soil minerals to near molecular size increased the solubility of  $Al_2O_3$  and  $SiO_2$  in dilute acids, sodium carbonate, and salt solutions. Sieling (10) reported that kaolin will be activated by ball milling. Perkins (8) indicated that prolonged grinding of kaolin might lead to complete disintegration of the mineral into  $Al_2O_3$ ,  $SiO_2$ , and  $H_2O$ .

The many papers on the extraction of metallic aluminum from clays indicates that clays and related soil minerals may be solubilized with the slow loss of certain elements by leaching and that it might be feasible to set up soil conditions to permit or encourage the conversion of one clay mineral to another.

The purpose of the present paper is to report on the effect of prolonged grinding, as a partial simulation of weathering, on particle size and chemical reactions of bentonite and muscovite, and to compare these results with similar data obtained by grinding kaolin.

## METHODS

Massive crystals of muscovite were separated into paper-thin sections, and impurities were picked out by hand. The purified mineral was then ground in a Wiley mill to pass a 1-mm screen, and the material thus obtained was used for additional grinding and treatments. Wyoming bentonite was obtained in rather large lumps, selected for purity, and ground in a Braun upright mill with carbo-

<sup>1</sup> Contribution No. 371, department of chemistry

run-dum plates to pass a 100-mesh screen. This material was used for additional grinding and treatments.

The minerals were analysed for  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  by A.O.A.C. methods (1). The  $\text{Al}_2\text{O}_3$  was precipitated by ammonium hydroxide as for  $\text{R}_2\text{O}_3$ . Particle size was determined by a Fisher sub-sieve sizer. Mechanical analysis was made

TABLE 1  
*Mechanical analysis of treated muscovite*

TREATMENT	AVERAGE PARTICLE SIZE*	MECHANICAL ANALYSIS†				
		<0.0002 mm.	0.0002- 0.00063 mm.	0.00063- 0.002 mm.	>0.002 mm.	Total
	μ	per cent	per cent	per cent	per cent	per cent
Wiley-milled 1-mm screen	6.00	0.0000	0.95	2.61	96.11	99.67
Dried absolute alcohol	6.60	0.00	0.74	2.34	97.03	100.11
Mortar-ground 1 hour	5.11	0.00	5.21	4.31	89.25	97.77
Ball-milled 4 weeks	1.00	9.02	10.65	8.27	74.11	102.05
Ball-milled 55 days	0.65	15.16	13.38	8.84	61.98	99.36
Mortar-ground 24 hours	0.50	18.40	16.14	14.77	50.04	99.35
Mortar-ground 72 hours	0.40	17.37	21.60	15.62	42.96	97.55

\* Data from sub-sieve sizer

† Water suspension and Stokes' law

TABLE 2  
*Reactions and composition of treated muscovite*

TREATMENT	BASE- EXCHANGE CAPACITY	0.1 N HCl TO TITRATE 5 GM. TO pH 2.5	0.01 N NaOH TO TITRATE 5 GM. TO pH 11.5	SWELLING IN H <sub>2</sub> O LAYER	SiO <sub>2</sub> * R <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>
		ml	ml			per cent	per cent
	mgm./100 gm			mm			
Wiley-milled 1-mm screen	1.86	7.5	16.0	4	1.91	46.8	41.5
Dried absolute alcohol	2.14	17.8	14.42	4	1.99	46.8	39.6
Mortar-ground 1 hour	5.50	25.0	17.60	4	1.81	46.4	43.6
Ball-milled 4 weeks	20.0	89.0	15.8	4	1.80	46.0	41.8
Ball-milled 55 days	53.07	323.7	20.5	4	1.99	44.1	37.7
Mortar-ground 24 hours	59.57	175.0	25.0	4	1.97	44.4	38.3
Mortar-ground 72 hours	64.00	260.00	25.0	4	2.02	43.0	36.3

\* Molecular ratio

by dispersing the mineral in a dilute ammonium hydroxide solution and separating the particles by sedimentation accelerated by a centrifuge. Calculation of sedimentation time required to precipitate the various sized particles was based on Stokes' law. Base-exchange capacity was determined by leaching the sample with neutral normal ammonium chloride solution until equilibrium was established, followed by removal of excess electrolyte with 80 per cent alcohol. The ammonium ion was released from the mineral with magnesium oxide and quantitatively determined by Kjeldahl distillation. The pH values were deter-

mined by the use of a glass electrode. Titration curves were obtained by suspending 5 gm. of the mineral in water, thoroughly mixing, and determining the pH values resulting from the addition of 0.1 N HCl or NaOH. A single titration curve was obtained in about 45 minutes.

TABLE 3  
Composition of muscovite separates

TREATMENT	<0.0002 mm.			0.0002-0.00067 mm.			0.00067-0.002 mm.			>0.002 mm.		
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub> * R <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub> * R <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub> * R <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub> * R <sub>2</sub> O <sub>3</sub>
	per cent	per cent		per cent	per cent		per cent	per cent		per cent	per cent	
Wiley-milled 1-mm screen				55.9	45.0	2.10	56.1	46.4	2.1	48.0	42.5	1.9
Dried absolute alcohol				44.4	39.4	1.9	46.6	37.1	2.2	46.5	42.2	1.9
Mortar-ground 1 hour				55.6	40.3	2.2	57.4	43.7	2.2	49.4	41.4	2.0
Ball-milled 4 weeks	35.9	34.7	1.8	42.9	40.3	1.8	43.3	41.4	1.8	45.8	39.5	2.0
Ball-milled 55 days	35.6	34.5	1.8	41.2	39.2	1.8	43.9	40.6	1.8	48.2	38.9	2.0
Mortar-ground 24 hours	44.3	38.6	1.9	45.2	36.2	1.9	44.7	36.5	2.1	44.1	38.5	2.0
Mortar-ground 72 hours	51.9	41.4	2.2	46.7	38.9	2.2	55.1	45.9	2.0	47.6	40.2	2.0

\* Molecular ratio

TABLE 4  
Mechanical analysis of treated bentonite

TREATMENT	AVERAGE PARTICLE SIZE*	MECHANICAL ANALYSIS†				
		<0.0002 mm.	0.0002-0.00063 mm.	0.00063-0.002 mm.	>0.002 mm.	Total
	μ	per cent	per cent	per cent	per cent	per cent
20 mesh	27.0	31.5	28.3	20.6	17.0	97.4
Heated 700°	25.0	0.0	0.0	1.4	100.5	101.9
Dried absolute alcohol	16.0	35.0	34.7	15.1	15.9	100.7
Mortar-ground 1 hour	6.1	40.0	24.5	15.7	16.0	96.2
Ball-milled 1 week	2.5	68.8	7.7	4.2	14.0	94.7
Mortar ground 24 hours	1.7	19.3	28.8	18.7	30.6	97.4
Mortar-ground 72 hours	1.0					

\* Data from sub-sieve sizer  
† Water suspension and Stokes' law

Swelling was determined during the mechanical separation of the mineral for the data in tables 1 and 4. Five grams of mineral was placed in a 450-ml. centrifuge tube and, after the first centrifugation of about 90 minutes to precipitate the particles coarser than 0.0002-mm diameter, the depth of the precipitated layer was measured.



## RESULTS

From the data presented it is clear that the several treatments of muscovite and bentonite radically alter the characteristics of these minerals. The data are in line with similar data reported for kaolin (8) and with data reported by other investigators. That grinding the minerals does not alter their chemical composition, except possibly the water content, is shown by  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  data in tables 2 and 5. The data indicate a greater alteration of the bentonite than of the muscovite by grinding. Possibly this is due to the simpler structure of the bentonite or a greater resistance to grinding by the muscovite.

Particle sizes determined on the muscovite and bentonite samples by a sub-sieve sizer which determines total surface area by resistance to the flow of a stream of air and also determined by sedimentation in water and subsequent drying at  $110^\circ$  are reported in tables 1 and 4. The data for the two methods agree rather well for the muscovite, but do not agree for the bentonite. As muscovite is ground for increasing lengths of time, the surface area by the sub-sieve sizer increases and the percentage of small particles increases. When bentonite is ground for increasing lengths of time, the surface area increases, but the percentage of small particles determined by water sedimentation does not increase regularly. This failure of agreement between the two methods suggests that continued grinding activates the bentonite particles, which when suspended in water polymerize into larger units. This agrees with data for kaolin (8).

That grinding muscovite and bentonite greatly alters the minerals is evident from the data in tables 2 and 4. The base-exchange capacity of muscovite was found to increase as particle size decreased, but that of bentonite decreased after the particles become smaller than about  $2\ \mu$  in diameter.

Equations similar to proposed decomposition equations for kaolin (8) might be written. A possible equation for bentonite would be  $\text{Al}_2(\text{Si}_4\text{O}_{10})(\text{OH})_2 \rightarrow \text{Al}_2\text{O}_3 + 4\text{SiO}_2 + \text{H}_2\text{O}$ . A similar equation might be written for muscovite.

Reaction of both muscovite and bentonite with acids and bases is greatly increased by grinding. Muscovite mortar-ground for 72 hours required 260 ml 0.1 N HCl to reduce 5 gm of water-suspended mineral to pH 2.5, whereas the unground muscovite required only 7.5 ml. Similar figures for 0.1 N NaOH required to adjust suspensions to pH 11.5 were 25 ml and 16.0 ml. Grinding muscovite increased the amphoteric nature of the mineral, as it became more reactive with acid and base. Bentonite mortar-ground 24 hours requires more acid and base to adjust the pH values of suspensions to 2.5 and 11.5 than does the unground bentonite. These data agree with those for kaolin (8).

Swelling data show that grinding muscovite does not change the volume of the mineral suspended in water. The swelling of bentonite, however, is considerably altered by grinding, as the volume of 5 gm of unground mineral is 14 ml, whereas the volume of 24-hour mortar-ground mineral is 7 ml. Bentonite dried with absolute alcohol had a swelling volume of 50 ml compared to 14 ml for the untreated mineral. This, however, was probably due to small amounts of alcohol retained by the mineral even though the mineral had been dried in a vacuum oven at  $100^\circ$  for 24 hours.



That the bentonite is decomposed into its molecular constituents by grinding is shown by the data in tables 3 and 6. The ground mineral was separated by water suspension and sedimentation, according to particle size. Sedimentation times were calculated by Stokes' law, and sedimentation was hastened by

TABLE 5  
Reactions and composition of treated bentonite

TREATMENT	BASE- EXCHANGE CAPACITY	0.1 N HCl TO TITRATE TO pH 2.5	0.1 N NaOH TO TITRATE TO pH 11.5	SWELLING IN H <sub>2</sub> O LAYER	SiO <sub>2</sub> * R <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>
	meq./100 gm.	ml	ml	mm		per cent	per cent
20-mesh	69.9	30.0	38.33	14.0	4.16	59.36	24.30
Heated 700°	21.6	17.5	29.00	4.0	4.14	66.63	27.4
Dried absolute alcohol	70.0	23.4	36.10	50.0	4.07	63.06	26.15
Mortar-ground 1 hour	69.7	32.0	35.93	14.0	4.34	60.06	23.53
Ball-milled 1 week	70.9	47.4	34.87	10.0	4.27	59.40	22.65
Mortar-ground 24 hours	66.9	120.0	47.67	7.0	4.20	59.13	23.90
Mortar ground 72 hours	20.7	?	?	?	?	?	?

\* Molecular ratio

TABLE 6  
Composition of bentonite separates

TREATMENT	<0.0002 mm			0.0002-0.00067 mm.			0.00067-0.002 mm.			>0.002 mm		
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub> * R <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub> * R <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub> * R <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub> * R <sub>2</sub> O <sub>3</sub>
	per cent	per cent		per cent	per cent		per cent	per cent		per cent	per cent	
Original	51.4	24.4	3.59	57.6	28.2	3.47	58.6	25.5	3.89	73.7	18.5	6.78
Heated 700°							56.6	26.9	3.59	62.3	21.1	4.90
Dried absolute alcohol	54.1	26.3	3.50	56.2	27.4	3.50	62.4	28.5	4.48	73.8	17.0	7.28
Mortar-ground 1 hour	51.8	24.6	3.49	56.9	27.4	3.53	60.1	25.6	3.96	74.5	16.3	7.68
Ball-milled 1 week	57.3	27.4	3.56	57.7	27.6	3.57	81.2	21.3	6.37	77.2	15.5	8.45
Mortar-ground 24 hours	46.1	21.3	3.67	56.4	26.5	3.60	59.6	24.6	4.12	62.7	22.7	4.70
Mortar-ground 72 hours												

\* Molecular ratio

centrifugation. Chemical analysis of the separates shows that the coarse particles contain a much higher percentage of silica than do the fine particles. This agrees with unpublished data for kaolin obtained from the separates reported by Perkins (8). The data for the muscovite do not show the change in composition as the particle size varies. In obtaining the separates, the ground mineral was suspended in water and centrifuged for the required time. This suspension and sedimentation was repeated until the supernatant liquid was clear, and the

liquid was evaporated. As the fine separates were obtained first, they would include all of the dissolved constituents.

#### SUMMARY AND CONCLUSIONS

Grinding alters the chemical and physical characteristics of muscovite and bentonite. It greatly increases the base-exchange capacity of muscovite and its reaction with acid and base. It activates bentonite so that aggregation or polymerization occurs when the mineral is suspended in water, and apparently larger particles are produced. Base-exchange capacity is decreased by prolonged grinding, which indicates decomposition of the mineral. Reaction with acid and base is greatly increased, and swelling in water suspension is decreased. The chemical composition of the fine particles shows that grinding increases the water solubility of the  $Al_2O_3$  without a similar increase in solubility of the  $SiO_2$ . Grinding permits a separation of the constituents of bentonite. Progressive weathering of clay minerals in the soil will undoubtedly permit similar differential solubilities followed by precipitation and thus alter the clay minerals.

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## RAPID ELECTRODIALYSIS OF SOILS IN DILUTE BORIC ACID SOLUTION<sup>1</sup>

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A number of investigators (1, 2, 3, 6) have demonstrated that electrodialysis may be employed to extract exchangeable cations from the soil, and the results obtained by this method have closely approximated those obtained by extraction with various slightly acid and neutral salt solutions. Bradfield (1) has pointed out that electrodialysis has a number of advantages over the solution-extraction methods. Among such advantages may be listed elimination of the solvent action of strong salt solutions and of the necessity for removing, or destroying, the extracting salt before determinations for the various cations can be made on the leachate. With the advent of the flame photometer this latter weakness in the neutral salt solution method assumes more importance. It has been found that accurate determinations for potassium cannot be made with this instrument on solutions of high sodium content and that ammonium salts clog up the instrument.

The principal disadvantage of electrodialysis has been the time consumed in extracting the cations from the soil. This investigation was undertaken in an effort to reduce this time factor, in the hope that the method of electrodialysis could be adapted to routine analyses of soils for available plant nutrients.

Preliminary investigations were undertaken to determine whether the desired results could be obtained through modification of existing types of cells which are employed in the electrodialysis of soils. Several experimental cells were constructed in which the distance between electrodes and the thickness of the soil compartment were both reduced to the minimum with which it was practical to work. Eventually a small cell of a type similar to the cell developed by Mattson (3), but constructed as a single unit, was selected as having the greatest possibilities. This cell was tested with soils of known exchangeable cation content, employing a variety of membranes. Filter paper (Whatman No. 2 grade) was finally selected as the most efficient membrane material for reducing the time of dialysis. Since this cell is the one used in the work reported in this paper, details for its construction are presented in the following section and in figure 1.

### DESCRIPTION OF ELECTRODIALYSIS CELL

The cell shown in figure 1 is made from Lucite sheet  $\frac{1}{4}$  inch thick. The sections were cut with a hack saw and were put together with plastic cement. The inside dimensions of the completed cell are  $1\frac{1}{2}$  by  $2\frac{1}{2}$  by  $2\frac{1}{2}$  inches, listed in order

<sup>1</sup> Paper of the Journal Series, New Jersey Agricultural Experiment Station, Rutgers University—the State University of New Jersey, department of soils.

of width, length, and depth. Before the cell was assembled, grooves  $\frac{1}{16}$  inch deep were sawed on the inside of the end pieces to receive the electrodes and side walls of the soil compartment. The distance between electrodes is  $\frac{3}{8}$  inch, and that between the side walls of the soil compartment is  $\frac{1}{2}$  inch. The electrodes and side walls of the soil compartment are cut to the same dimensions, 2 by  $2\frac{1}{2}$  inches. The anode electrode is of perforated platinum sheet, and the cathode electrode is of perforated nickel sheet. The side walls of the soil compartment were cut from sheet Bakelite  $\frac{1}{16}$  inch thick and the sections perforated with a drill. Slides from photographic plate holders are a convenient source of this material. The side walls of the soil compartment should be cemented into their grooves.

The membrane is cut from filter paper into rectangular shape, with dimensions of  $2\frac{1}{2}$  by  $4\frac{1}{2}$  inches. This sheet is folded once along the shorter axis and is inserted into the soil chamber with the folded edge at the bottom. To hold the membrane securely against the sides of the soil chamber, a three-sided frame of Lucite or Bakelite is inserted between the folds of the membrane and pressed firmly against the bottom of the cell, with the open side of the frame at the top. This frame is conveniently made by sawing out the inside section of a  $2\frac{1}{2}$ - by  $2\frac{1}{2}$ -inch piece of  $\frac{1}{4}$ -inch sheet so as to leave a  $\frac{1}{4}$ -inch strip around the two longer sides and across one end. The frame can then be sanded down to make it fit snugly between the walls of the soil compartment.

To facilitate removal of solution from the cell, a  $\frac{3}{8}$ -inch hole is drilled into the bottom of either the anode or cathode chamber and a  $\frac{3}{8}$  inch long piece of plastic tubing cemented into the hole. The plastic tubing is then capped with a piece of soft rubber tubing which may be closed with an ordinary pinchcock. If it is desired to keep the anode and cathode solutions separate, tubes similar to the above should be inserted into both chambers. In the work reported here the two solutions were drawn off together and determinations run on the composite solution. Drainage of the cell is speeded up if the membrane enclosing the soil is raised from the bottom of the cell after the outlet tube is opened.

The cell is completed by fitting two small electrical binding posts to one end, as shown in figure 1. The cell is designed to electrolyse 5 gm. of soil and holds 80 ml. of solution. In operation, it is connected in series with a 40-watt light bulb, and a potential difference of 100 volts direct current (regulated by rheostat) is applied to the electrodes for 20 minutes. With the soils studied, the amperage of the cell seldom exceeded 0.2, and the temperature of the solutions varied between 40° and 50°C.

#### EXPERIMENTAL

With the first series of soils subjected to electrodialysis with the cell, it was evident that extraction of exchangeable calcium, potassium, and sodium was being effected in a satisfactory manner within a 20-minute period. Only traces of magnesium, however, could be detected in the cathode solutions from soils known to contain an appreciable amount of this element in the exchange complex. Lengthening the period of dialysis did not overcome the difficulty. By changing

the solutions and adding fresh portions of distilled water at 20-minute intervals, it was found that the bulk of the exchangeable magnesium could be detected in the solutions from the second and third periods. This did not solve the problem, since it again introduced the time factor.

The fact that magnesium becomes mobile in the electrodialysis of soils only after the bulk of the cations calcium, potassium, and sodium have been removed has been noted by Mattson (4), Wilson (7), and others. This retarded mobility of magnesium has been attributed to the strongly alkaline reaction that develops in the cathode membrane and the soil layer immediately adjacent to this membrane in the early stages of electrodialysis. This results in formation of magnesium compounds which, under these conditions, are relatively more stable than those of other cations. After Sassafras sandy loam had been electro-

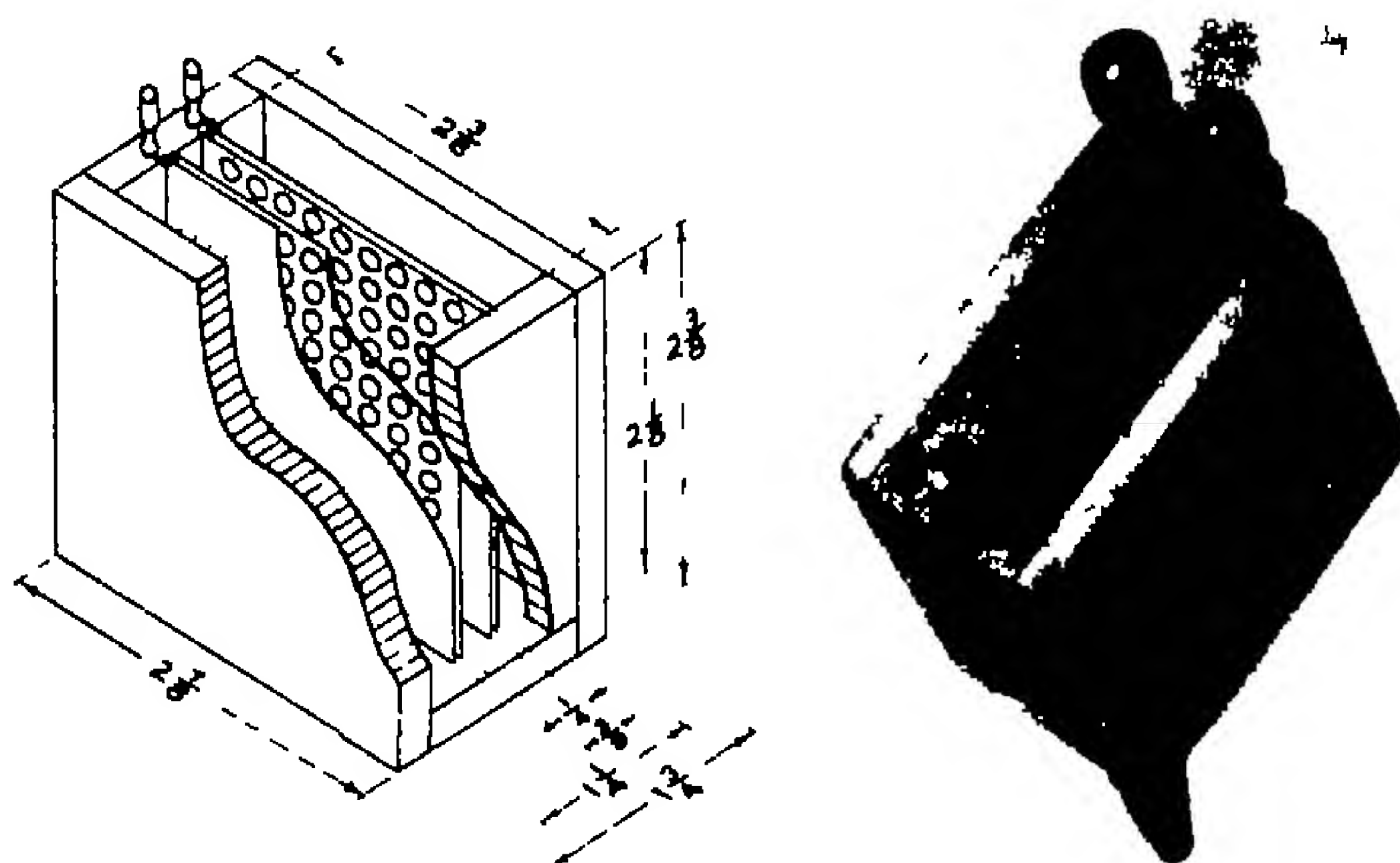


FIG. 1. CONSTRUCTION DIAGRAM AND COMPLETED ELECTRODIALYSIS CELL

dialyzed for 20 minutes the cathode solution was found to have a pH of 11.0. Although but a trace of magnesium could be detected in this solution, an acid extract of the cathode membrane gave a strong test for magnesium. The composite pH of the soil had been reduced from 6.2 to 4.7, but the cathode membrane was still highly alkaline as shown by colorimetric test.

It is evident that without some factor to reduce this highly alkaline reaction exchangeable magnesium ions cannot be quantitatively extracted from a soil by electrodialysis without a change of solution. The possibility of using a weak solution of a slightly dissociated acid in place of distilled water as the dialyzing solution appeared to have possibilities in this direction. Boric acid, with a dissociation constant of  $6.4 \times 10^{-10}$  at  $25^\circ\text{C}$ , was selected for trial. Solutions of the acid at various strengths were tried, and 0.05 N solution was chosen as most satisfactory. With a pH of 5.4 this solution would not be sufficiently acid to affect seriously the solubility of the soil minerals. Table 1 presents compar-

trive data obtained in electro dialyzing 5-gm portions of Sassafras sandy loam for 20-minute periods, distilled water being used as the dialyzing solution in one instance, and 0.05 N boric acid in the other.

It will be noted that the greatest difference between the two dialyzing solutions was in their effect upon the pH of the cathode solutions and cathode membranes. The small difference in the pH of the soils after dialysis is attributed to inclusion of the soil immediately adjacent to the cathode membrane in the instance where water was used as the dialyzing solution. The reduction in pH in the cathode zone of the cell was apparently sufficient to accomplish the purpose desired,

TABLE 1  
*Comparison of distilled water and 0.05 N boric acid as dialyzing solutions in electro dialysis of Sassafras sandy loam*

	ELECTRODIALYSIS WITH	
	Distilled water	0.05 N boric acid
pH of cathode solution	11.0	8.2
pH of anode solution	3.5	3.5
pH of soil after electro dialysis	4.7	4.4
pH of cathode membrane*	Strongly alkaline	Slightly alkaline

\* Estimated colorimetrically.

TABLE 2  
*Characterization of soils used for comparison of methods*

SOIL TYPE		pH	EXCHANGE CAPACITY meq/100 gm	ORGANIC MATTER %
1	Dutchess shale loam	5.7	26.42	8.1
2	Washington loam	5.3	14.40	4.1
3	Chenango fine sandy loam	5.8	13.70	4.1
4	Sassafras loam	6.5	13.70	4.0
5	Sassafras sandy loam	6.5	9.08	2.8
6	Sassafras sandy loam	6.6	8.90	2.9
7	Sassafras sandy loam	6.2	5.74	1.9
8	Sassafras sand	4.8	2.60	1.3

since a strong test for magnesium was obtained in the cathode solution from the electro dialysis with boric acid.

To subject the cell and method to further tests, 5-gm portions of eight representative New Jersey soils were electro dialyzed for 20-minute periods and the solutions analyzed for calcium, magnesium, potassium, and sodium. Data which characterize the soils selected are presented in table 2. The analytical methods employed for determining the exchange capacity and the exchangeable cation content were those described by Peech and associates (5), except that potassium and sodium were determined with the flame photometer. Organic matter was determined by a previously described method, and all pH determinations were made with the glass electrode unless otherwise specified.



Table 3 presents a comparison of the exchangeable-cation content of the eight soils as determined by extraction with neutral normal ammonium acetate in one instance, and by electrodialysis for 20 minutes with 0.05 *N* boric acid in the other.

The data presented in table 3 show reasonably close agreement between the two methods except in the case of sodium. From two to four times as much of this element was found in the solutions from electrodialysis as in the ammonium acetate extracts. Electrodialysis removed more sodium than potassium from six of the eight soils, whereas only soil 4 released more sodium than potassium to the ammonium acetate solution. It is possible that part of the sodium was lost in driving off the ammonium acetate, but this does not explain why there was not a similar loss of potassium. If the quantity of the element removed by electrodialysis represents the exchangeable fraction, however, it is evident that much

TABLE 3

*Comparison of exchangeable-cation content as determined by extraction with neutral normal ammonium acetate and by electrodialysis in 0.05 *N* boric acid*

SOIL NUMBER	EXTRACTION WITH AMMONIUM ACETATE				ELECTRODIALYSIS			
	Ca	Mg	K	Na	Ca	Mg	K	Na
	m.e. *	m.e.	m.e.	m.e.	m.e.	m.e.	m.e.	m.e.
1	15.80	1.76	0.45	17	15.88	1.73	0.42	40
2	5.28	1.00	0.25	10	5.00	0.93	0.20	28
3	8.16	0.78	1.25	12	8.62	0.80	1.22	32
4	6.20	2.32	0.11	12	6.12	1.94	0.08	24
5	5.12	1.80	0.22	09	4.88	1.60	0.19	24
6	7.24	0.72	0.13	10	6.80	0.75	0.12	22
7	4.56	0.52	0.10	07	4.00	0.63	0.08	28
8	0.72	0.10	0.14	06	0.88	0.13	0.11	16

\* m.e. per 100 gm

more consideration must be given to exchangeable sodium in the heavily fertilized soils of New Jersey and other eastern states than has been given to it in the past.

#### DISCUSSION

The substitution of 0.05 *N* boric acid for distilled water as the dialysing solution in the electrodialysis of soils increases the initial concentration of hydrogen ions in the solution and thereby effects a more rapid replacement of the exchangeable cations by hydrogen. This increase in acidity is not sufficiently great, however, to affect seriously the solubility of the normally inert soil minerals, and the lowest pH reached during the process of electrodialysis is no lower than that of the anode solution in the final stages of electrodialysis with distilled water. Boric acid appears to be especially suitable for such use, since the pH of a 0.05 *N* solution is only 5.4, considerably higher than that of any other mineral acid of similar concentration.

A more important factor in the use of boric acid is its influence upon the rate of removal of magnesium from the soil. This is apparently effected by the reduc-



tion of the high alkalinity normally produced in the cathode chamber and in the cathode membrane

Since the only purpose of membranes in dialysis is to separate the material being dialyzed from the dialyzing solution, the use of filter paper as a membrane material is warranted. This speeds up the rate of removal of the cations considerably, and if care is taken to provide a close fit for the frame that is inserted to hold the filter paper firmly in the soil chamber, no solid material will be found in the solutions.

Combining the anode and cathode solutions at completion of electro-dialysis appears to produce no complications and saves considerable time. Calcium, potassium, and sodium determinations may be run on the combined solutions with the flame photometer. As magnesium determinations with this instrument have not proved satisfactory to date, this element is estimated colorimetrically. With the method herein described, it is possible to extract and determine quantitatively the content of exchangeable calcium, magnesium, potassium, and sodium in a soil within 45 minutes.

Preliminary work indicates that the method may also have possibility in determining the available phosphorus content of soils. Although the electro-dialyzable phosphorus is not so completely removed within the 20-minute period of dialysis as are the cations, soils known to be low in available phosphorus have been found to release very little of the element, whereas soils of high phosphorus content release the element readily.

With a battery of 10 or more cells it should be possible to obtain quantitative data on the exchangeable-cation content of soils within as little time as is now required by the customary methods employed in rapid soil testing. Present plans are to adopt the method for this purpose in New Jersey.

#### SUMMARY

A modified type of cell for electro-dialysis of soils is described.

Data are presented to demonstrate that substitution of 0.05 *N* boric acid for distilled water in the electro-dialysis of soils increases the rate of removal of exchangeable cations so that quantitative results may be obtained within a 20-minute period of electro-dialysis without change of dialyzing solution.

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# YIELD AND COMPOSITION OF ALFALFA AS AFFECTED BY VARIATIONS IN THE CALCIUM-MAGNESIUM RATIO IN THE SOIL

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From the standpoint of nutritive value, the mineral content of forage crops is highly important. This is especially true of P, which for the country as a whole is more often than any other element the limiting factor in nutritional deficiency troubles in grazing livestock and in low crop production. The factors involved in the uptake of P by plants and the P relationships between soils and plants are, therefore, of great practical as well as theoretical interest.

The theory was proposed by Loew (10) that one of the functions of Mg in the plant is to serve as a carrier of P, transporting it within the plant to the points where it is synthesized into organic compounds. Few studies of the effects of additions of Mg to soil upon the utilization of P by plants have been reported. Kellog (8) concluded that, because of Mg deficiency, some soils may not respond to P fertilization. Truog (16) considered that not only must plants be supplied with sufficient readily available Mg but there must be a proper balance between Ca and Mg for efficient utilization of P. Recently Truog *et al.* (17) reported greatly increased concentration of P in garden peas from applications of dolomitic limestone to soil and from increases in Mg level in sand-solution cultures, however, interpretation of the results is complicated by the fact that changes in pH from 5.3 to 6.5 and 7.5 may have affected the availability of P in the soil. Beeson, Lyon, and Barrantine (4) reported a positive correlation between Mg and P in tomato leaflets but thought a causal relationship questionable. Bartholomew (2) found such variation in effect when Mg was applied with the more soluble phosphatic fertilizers that no significant conclusions could be drawn. Willis, Piland, and Gay (18) concluded that there were no significant differences in the effects of Ca and Mg upon P absorption.

The chief object of the present experiment was to study the effects of variations in the amount of available Mg in the soil upon the concentration of P and other minerals in alfalfa. Since the soil has a definite exchange capacity, if the amount of any one cation is changed, that of at least one other cation (either a base or H) must be varied reciprocally or the amount of soil available to the plant must be increased or decreased. If one of these is not done, the capacity of the soil to adsorb nutrients may be exceeded, with the result that some of the nutrients will be present in the adsorbed condition and others as free salts, or, if leaching can occur, nutrients in excess of the exchange capacity of the volume of soil occupied by the roots will pass beyond the root zone and be lost to the plant.

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These considerations have frequently been overlooked in soil studies. In the present study it was decided to hold constant the amount of soil, the concentration of the H ion, or pH, and all nutrients other than Mg and Ca, thus resulted in variations in the Ca-Mg ratio.

Loew's proposal (10, 11) that a definite Ca-Mg ratio in the soil is required for optimum growth of each crop prompted much discussion and research. The critical review of Lipman (9) and the investigations of Moser (14) and others have led to the conclusion that there is no "best" Ca-Mg ratio in the soil for the growth of any crop. Little or no attention has been given to the effects of variations in the ratio upon the mineral or organic composition of plants.

In the experiment reported here soils having exchangeable ions in known, definite amounts were used. Such soils can be prepared by several methods, differing in simplicity and in practical advantages and disadvantages. They have been prepared by titration of H-clay with suitable quantities of metal hydroxides (1), by combining homionically saturated soils in proportions to give the desired ion relationships (6), and by mixing appropriate amounts of carbonates and bicarbonates with acid soil in a manner analogous to liming (12). No direct comparison of these methods has been reported, so far as is known. In this study, therefore, the last two of these methods of soil preparation were employed for comparison. To make the comparison more valid, a uniform lot of H-soil, from which the exchangeable bases initially present had been removed by acid extraction, was used as the starting material for both methods. Ca and Mg were varied reciprocally over a wide range, embracing six Ca-Mg ratios. In view of the possibility that the effect of the Ca-Mg ratio on P uptake might vary with the level of P, that element was supplied at two levels. The three variables were combined in a  $6 \times 2 \times 2$  (6 Ca-Mg ratios, 2 P levels, 2 methods of preparation) factorial experiment, with four complete replications.

#### EXPERIMENTAL MATERIALS AND PROCEDURES

##### *Preparation of soils*

Soil from the A<sub>p</sub> horizon of Mardin loam was leached with 0.05 N HCl to prepare a large quantity of H-soil. This was divided into three lots. From one lot Ca-, Mg-, and K-soils were prepared by leaching with the respective neutral normal acetates and washing out excesses of the cation with distilled water. A P-soil was prepared by leaching the second lot with H<sub>3</sub>PO<sub>4</sub>. The third lot was used as H-soil. The exchangeable cations present in the Ca-, Mg-, and K-soils were, respectively, 15.3, 15.1, and 11.5 m.e. per 100 gm. The H- and P-soils had total P contents of 1.2 and 6.1 mgm. per gram, respectively, 4.9 mgm. P per gram was "fixed" during H<sub>3</sub>PO<sub>4</sub>-leaching.

From these homionic soils two series (called "adsorbed series" and "carbonate series," as described below) of soil-sand mixtures of variable Ca-Mg ratios and P levels were prepared and placed in 2-gallon pots, without drains. Each pot contained a total weight of 4½ pounds of soil and 15 pounds of silica sand, thoroughly mixed, the sand being added to increase the volume and provide favorable growing conditions for the roots. (Hereinafter these mixtures will be called

“soil,” and each will be identified as 1/4, 1/1, etc , according to Ca-Mg ratio, as set forth in table 1 ) Two levels of P in each series were obtained by supplying the following as 1/2 pound of the 4 1/2 pounds total soil in each pot P<sub>1</sub> level, 1/2 pound of P-soil and 1/2 pound of H-soil, P<sub>2</sub> level, 1/2 pound of P-soil The adsorbed series was prepared by mixing the above amounts of P- and H-soils with 1/2 pound of K-soil and a total of 3 1/2 pounds of Ca- and Mg-soils, so apportioned as to give the desired Ca-Mg ratios For the carbonate series, to the aforementioned quantities of P- and H-soils were added 4 pounds of H-soil and the salts CaCO<sub>3</sub>, MgCO<sub>3</sub>, and KHCO<sub>3</sub> in amounts equivalent to the exchangeable Ca, Mg, and K present in the adsorbed series. Powdered S and solutions of minor elements were added to the surface of the soil in all pots at the following rates per 2 million pounds of soil (basis 4 1/2 pounds per pot) S, 100 pounds, borax, 20 pounds, and the sulfates of Cu, Mn, Zn, and ferrous Fe in amounts chemically equivalent to

TABLE 1  
*Exchangeable bases and cation ratios initially present in pots of soil of adsorbed and carbonate series*

soil	Ca			Mg			K			CATION RATIOS		
	Ca	Mg	K	Ca	Mg	K	Ca	Mg	K	Ca/Mg	Ca/K	Mg/K
	m.s./100 gm.	m.s./100 gm.	m.s./100 gm.	m.s./pot	m.s./pot	m.s./pot	lb *	lb *	lb *			
1/4	2 35	9 39	1 27	48	192	26	943	2292	1000	1/4	1 8/1	7 4 /4
1/1	5 92	5 92	1 27	121	121	26	2386	1430	1000	1/1	4 6/1	4 6 /1
4/1	9 48	2 35	1 27	194	48	26	3818	572	1000	4/1	7 5/1	1 8 /1
8/1	10 56	1 32	1 27	216	27	26	4226	327	1000	8/1	8 8/1	1 0 /1
16/1	11 14	0 68	1 27	228	14	26	4485	171	1000	16/1	8 8/1	0 65/1
32/1	11 50	0 37	1 27	235	7 5	26	4620	89	1000	32/1	9 1/1	0 27/1

\* Per 2 million pounds

the borax. To ensure a normal microflora, a small amount of a water extract of a fertile cultivated soil was added to each pot

Data on the exchangeable bases and cation ratios initially present in the soils are set forth in table 1

Determinations by the modified Truog method<sup>1</sup> showed approximately 80 and 160 pounds of available P per 2 million pounds<sup>2</sup> at the P<sub>1</sub> and P<sub>2</sub> levels, respectively The pH of the soils was determined 5 weeks after potting and found to be practically uniform at values of approximately 6.2, with only 4 of 96 pots giving values varying as much as 0.3 pH unit from this figure, at the end of the experiment the pH values showed essentially uniform decreases of about 0.3 unit

The amount of water retained by the soil-sand mixtures under tensions of 100

<sup>1</sup> Methods of soil analysis for soil fertility investigations Prepared by a committee on uniform methods of soil analysis, Michel Peck, chairman Mimeographed by Division of Soils, Fertilizers and Irrigation, U S Dept Agr, March 1945

<sup>2</sup> Based on 4 1/2 pounds of soil per pot To calculate on the basis of total weight of sand and soil, multiply these values by 0.23

cm of water was determined with Richards and Fireman's pressure-plate apparatus (15) to be 9.5 per cent

#### *Cultural methods*

The 96 pots of soil were arranged in a greenhouse in four randomized blocks of 24 pots each. On May 27, 1946, 30 inoculated Grimm alfalfa seeds were planted in each pot. The resulting plants were thinned to four. All irrigations were made with distilled water. Soil moisture fluctuated through a relatively small tension range (usually not higher than 1 atmosphere). At frequent intervals the pots were weighed and quantities of water calculated to lower the moisture tension uniformly to 100 cm of water or less were added. The first harvest of alfalfa was made on August 3, when a few blooms had appeared on the plants, the second harvest, at a similar stage of maturity, was made on September 14. The roots were harvested at the end of the experiment.

#### *Analytical methods*

After being dried at 65°C and weighed, the alfalfa from each pot was ground and analyzed for P, Ca, Mg, K, and N, according to the procedure described by Kelley, Hunter, and Sterges (7). Lignin analyses on the first crop were made by a modification of the method of Ellis, Matrone, and Maynard (5). The data were treated statistically by the analysis of variance method. Determinations of the pH of the soil in each pot were made by means of the glass electrode.

### RESULTS AND DISCUSSION

The data on yield and chemical composition of the alfalfa are summarized in tables 2 and 3. The influence of the factors of variation upon yield and composition, as determined by analyses of variance, is presented in table 4.

#### *Yield of alfalfa*

In accordance with the conclusions of Lapman (9) and Moser (14) that there is no "best" Ca-Mg ratio for optimum growth of plants, the yield of alfalfa and weight of roots were not significantly affected by variations of Ca-Mg ratio in the soils of this experiment, although these ratios covered an extreme range. Hunter, Toth, and Bear (6) found, similarly, that over a wide range, variations in Ca-K ratio in the soil had little effect on alfalfa growth. The Ca-Mg ratios of most agricultural soils are included within the range 1/1 to 8/1 (14), values as low as 1/4 or as high as 32/1 are seldom encountered in natural soils, nor are they ordinarily produced by liming.

The method of soil preparation had highly significant effects upon the yield of the first crop and the roots, the lowest yield being produced by the soils of the carbonate series. The reason for this is not known, but it was possibly due to delay in reaction of the added carbonates with the H-soil. The yields from the adsorbed and carbonate soils were much more nearly similar in the second crop than in the first (table 2). The alfalfa was seeded 4 days after mixing of the soils, determinations made approximately 5 weeks later showed the soils to have



TABLE 2  
Summary of data on yield and composition of alfalfa  
Means for four replicates

Ca/Mg Ratio	SOIL PREPARA- TION SERIES*	DRY WEIGHT			P		Ca		Mg		K		N		LIGNIN	TOTAL CATIONS	
		1st†	2nd	Roots	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd		1st	2nd
		gm.	gm.	gm.	%	%	%	%	%	%	%	%	%	%		m.e./ 100 gm.	m.e./ 100 gm.
P <sub>1</sub> Level																	
1/4	A	5.3	6.3	7.0	0.22	0.26	0.50	0.67	0.66	0.67	2.79	3.23	2.74	3.08	6.08	164	170
	C	2.9	4.7	4.8	0.23	0.30	0.58	0.71	0.55	0.63	2.23	3.23	3.13	3.40	5.06	164	174
	Mean	4.1	5.5	5.9	0.23	0.28	0.57	0.69	0.60	0.65	2.51	3.27	2.93	3.28	5.57	164	172
1/1	A	5.3	6.3	6.2	0.25	0.30	1.24	1.24	0.34	0.48	2.40	2.87	2.88	3.23	6.06	151	174
	C	4.3	6.1	6.3	0.27	0.30	1.06	1.10	0.27	0.51	2.73	3.04	3.00	3.28	6.55	164	179
	Mean	4.7	6.2	7.2	0.26	0.29	1.15	1.21	0.31	0.49	2.56	2.95	2.93	3.25	6.30	157	176
4/1	A	4.9	5.8	6.5	0.23	0.24	1.61	1.64	0.27	0.24	2.06	2.74	2.97	3.30	5.06	153	179
	C	3.6	5.5	5.9	0.23	0.29	1.50	1.35	0.24	0.31	2.43	2.71	2.86	3.29	6.00	153	164
	Mean	4.2	5.6	6.2	0.23	0.26	1.55	1.51	0.25	0.28	2.24	2.72	2.91	3.24	5.53	153	171
8/1	A	4.8	5.8	6.7	0.19	0.23	1.57	1.77	0.19	0.20	2.45	2.68	2.66	3.08	6.36	173	183
	C	2.7	5.7	6.1	0.23	0.27	1.41	1.25	0.21	0.29	2.67	2.67	2.91	3.31	6.06	143	166
	Mean	4.2	5.7	6.4	0.21	0.25	1.49	1.51	0.20	0.27	2.56	2.75	2.78	3.19	6.21	158	180
16/1	A	4.8	6.1	6.5	0.20	0.24	1.86	1.83	0.17	0.23	2.17	2.55	2.61	3.13	6.19	165	184
	C	4.0	5.1	5.2	0.24	0.28	1.56	1.54	0.18	0.26	2.38	2.79	2.84	3.35	5.55	153	171
	Mean	4.4	5.6	5.8	0.22	0.26	1.71	1.68	0.17	0.25	2.27	2.67	2.72	3.24	5.87	157	177
32/1	A	4.7	6.1	5.7	0.20	0.26	1.77	1.74	0.13	0.20	2.38	2.92	2.80	3.09	5.74	157	175
	C	4.0	6.1	5.5	0.23	0.25	1.44	1.44	0.15	0.24	2.29	2.88	2.60	3.31	6.08	146	166
	Mean	4.3	6.1	5.6	0.21	0.27	1.61	1.59	0.14	0.22	2.33	2.90	2.74	3.17	5.91	151	171
P <sub>2</sub> Level																	
1/4	A	4.6	5.7	6.9	0.33	0.43	0.63	0.70	0.56	0.60	2.60	3.26	2.99	3.23	6.33	143	173
	C	4.0	5.5	6.7	0.41	0.44	0.43	0.57	0.58	0.66	2.63	2.80	2.68	3.48	6.22	127	151
	Mean	4.3	6.1	6.8	0.37	0.43	0.55	0.63	0.55	0.63	2.64	3.03	2.83	3.40	6.28	140	162
1/1	A	5.2	6.4	6.2	0.23	0.34	1.16	1.10	0.34	0.51	2.23	3.02	2.53	3.23	6.05	145	175
	C	4.3	5.8	6.9	0.35	0.29	1.04	1.09	0.26	0.53	2.55	2.99	3.95	3.43	5.94	146	171
	Mean	4.7	6.1	7.5	0.31	0.31	1.10	1.12	0.30	0.52	2.44	2.95	2.80	3.33	6.20	145	173
4/1	A	5.1	6.4	7.7	0.27	0.27	1.45	1.57	0.22	0.22	2.37	2.81	2.60	3.29	6.29	151	176
	C	4.4	6.4	6.4	0.29	0.23	1.41	1.26	0.26	0.34	2.26	2.75	2.53	3.53	5.32	162	187
	Mean	4.7	6.4	7.0	0.28	0.24	1.44	1.47	0.24	0.28	2.31	2.78	2.78	3.45	6.40	151	171
8/1	A	4.7	6.2	7.4	0.26	0.24	1.53	1.61	0.19	0.26	2.17	2.58	2.78	3.30	6.12	130	170
	C	4.5	6.0	6.6	0.29	0.22	1.45	1.50	0.20	0.20	2.51	2.59	2.78	3.41	6.03	153	167
	Mean	4.6	6.1	7.0	0.27	0.23	1.51	1.55	0.19	0.23	2.34	2.73	2.78	3.35	6.07	151	168
16/1	A	5.1	6.6	7.0	0.26	0.24	1.65	1.68	0.15	0.24	2.12	2.89	2.67	3.19	5.89	148	178
	C	4.1	5.7	6.6	0.28	0.20	1.38	1.51	0.16	0.20	2.30	2.68	2.90	3.36	6.45	141	170
	Mean	4.6	6.1	6.8	0.27	0.22	1.51	1.59	0.15	0.22	2.21	2.77	2.78	3.27	6.12	144	173
32/1	A	5.2	6.5	6.5	0.24	0.20	1.51	1.59	0.12	0.23	2.19	2.70	2.59	3.08	6.09	136	181
	C	5.1	6.9	6.7	0.26	0.24	1.57	1.51	0.14	0.26	2.21	2.68	2.68	3.41	6.51	145	173
	Mean	5.1	6.7	6.6	0.25	0.22	1.54	1.75	0.13	0.24	2.20	2.69	2.63	3.19	6.31	151	176

\* A indicates adsorbed series, C carbonate series  
† 1st and 2nd refer to harvests.

similar pH values. The weights of both crops and of the roots were significantly affected by the level of P, the higher P level producing the higher yields. At

TABLE 3  
Summary of means for factors of variation

FACTOR	NUMBER DATA AVAIL- ABLE	DRY WEIGHT			P		Ca		Mg		N		K		LIG- NIN	TOTAL CATIONS	
		1st*	2nd	Roots	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd		1st	2nd
		gm.	gm.	gm.	%	%	%	%	%	%	%	%	%	%		m.e./ 100 gm.	m.e./ 100 gm.
Ca/Mg ratio																	
1/4	16	4.3	5.8	6.4	0.31	0.36	0.86	0.66	0.26	0.37	2.96	3.24	2.34	2.10	6.24	146	167
1/1	16	4.7	6.1	7.4	0.30	0.33	1.13	1.17	0.34	0.51	2.86	3.33	2.59	2.66	6.23	145	175
4/1	16	4.5	6.0	6.8	0.26	0.30	1.30	1.40	0.25	0.33	2.85	3.34	2.30	2.73	6.14	154	173
8/1	16	4.4	6.6	6.7	0.24	0.28	1.53	1.54	0.20	0.26	2.78	3.27	2.40	2.75	6.20	156	169
16/1	16	4.5	6.9	6.3	0.24	0.28	1.61	1.64	0.16	0.26	2.75	3.26	2.34	2.76	6.07	151	175
32/1	16	4.7	6.4	6.1	0.24	0.28	1.66	1.67	0.14	0.23	2.86	3.18	2.26	2.77	6.11	151	175
Soil prepara- tion																	
Adsorbed	48	5.0	6.2	7.6	0.24	0.31	1.43	1.45	0.26	0.37	2.73	3.19	2.33	2.60	6.21	154	177
Carbonate	48	4.1	5.9	6.3	0.26	0.33	1.24	1.27	0.26	0.36	2.89	3.26	2.23	2.53	6.26	149	167
P level																	
P <sub>1</sub>	48	4.3	5.8	6.3	0.23	0.27	1.37	1.37	0.26	0.37	2.83	3.24	2.43	2.91	6.16	155	173
P <sub>2</sub>	48	4.7	6.3	7.0	0.30	0.34	1.30	1.34	0.27	0.36	2.82	3.34	2.26	2.80	6.31	148	171

\* 1st and 2nd refer to harvests

TABLE 4  
Significance of effects of factors of variation upon growth and composition of alfalfa, as shown by the F test

	DRY WEIGHT			P		Ca		Mg		K		N		TOTAL CATIONS		LIGNIN
	1st	2nd	Roots	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	
				per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent			per cent
Ca/Mg ratio				**	**	**	**	**	**	**	**	**	**			
P level	*	**	**	**	**	*		*				*	**			
Soil preparation	**		**	**		**	**			**		**	**	*	**	
Replication	**	**		**	**	**	*				**	**		**	**	
Ca/Mg × PL				*												
PL × SP	*															

\* Indicates significance at odds of 19 to 1  
\*\* Indicates significance at odds of 99 to 1  
† 1st and 2nd refer to harvests

each harvest there were differences in yield associated with replication, probably because of variation in environmental conditions with location in the greenhouse



*Chemical composition of alfalfa*

*Percentage of P* At each harvest the Ca-Mg ratio had highly significant effects upon the percentage of P in the alfalfa. As is shown in table 3, however, the percentage of P was affected only slightly by decreasing the Ca-Mg ratio of the soil from 32/1 to 4/1—within the range in which Ca exceeded Mg, and significant increases in P occurred only when the amount of exchangeable Mg in the soil was increased sufficiently to be equivalent to or greater than the amount of Ca. In the first alfalfa crop, the P content was constant at 0.24 per cent through the three highest Ca-Mg ratios but rose significantly to 0.29 and 0.31 per cent for the 1/1 and 1/4 ratios, respectively, similarly, in the second crop it increased from 0.28 to 0.33 and 0.36 per cent, respectively, for the same ratios.

The most important factor determining the P content of the plants was the level of P in the soil. In each crop the higher level of P resulted in an increase of about 30 per cent in percentage of P. At the lower level of P the effect of variations in the Ca-Mg ratio was smaller than at the higher level (table 2). In the first crop the interaction of Ca-Mg  $\times$  P level was statistically significant.

Figure 1 shows the relationship between the contents of Mg and P in the plant on a chemical equivalent basis. The P is calculated as millimoles. It is evident from the graph, and from the data of table 3, that there was no close correlation between the uptake of the two elements. Although the percentage of P in the plant increased significantly as the Ca-Mg ratio in the soil decreased from 4/1 to 1/4, the rate of increase was much less than that for the percentage of Mg. As set forth in tables 1 and 3, Mg varied from 0.37 to 2.35 m.e. per 100 gm. in the soil (32/1 to 4/1 ratios), and from 0.14 to 0.25 per cent and 0.22 to 0.33 per cent in the plant (first and second crops, respectively) without producing any significant effects upon P uptake.

*Percentages of Ca and Mg* Though the Ca-Mg ratio in the soil had no significant influence upon the weight of crop produced, it had highly significant effects upon the percentages of Ca and Mg in the alfalfa. The data are similar to those obtained in another experiment (6), where variations from 1/1 to 100/1 in the Ca-Mg ratio in the soil had little effect upon alfalfa yield but produced large differences in the contents of Ca and K. The percentage of Ca increased markedly as the Ca-Mg ratio increased from 1/4 to 4/1, as shown by the data of table 3, further increases in the ratio brought about only slight increments in Ca content. Mg was absorbed to a much lesser extent than Ca, and decreased rapidly as the amount of available Mg decreased with increasing Ca-Mg ratio. The soils of the adsorbed series delivered significantly more Ca to the plants in each crop than those of the carbonate series; the percentage of Mg was unaffected by method of soil preparation.

*Percentage of K* In each alfalfa crop the Ca-Mg ratio had highly significant effects upon the percentage of K, the highest percentage of K being associated with the lowest Ca-Mg ratio. Since the total of Ca and Mg was constant throughout all Ca-Mg ratios and the percentage of K declined with increasing ratio, it would appear that the antagonistic effect of Mg on K absorption is less than that of Ca. At the first harvest the soils of the adsorbed series produced plants of significantly lower K content than those of the carbonate series.

*Percentage of N* The percentage of N was significantly affected by Ca-Mg ratio and method of soil preparation. In the first crop the 1/4 soil produced plants of significantly higher N content than the 32/1 soil, there was gradually decreasing N content with increasing Ca-Mg ratio, but the differences were significant only between the highest and lowest ratios. The same trend in the effect of decreasing Ca-Mg ratio was evident in the second crop. The soils of the

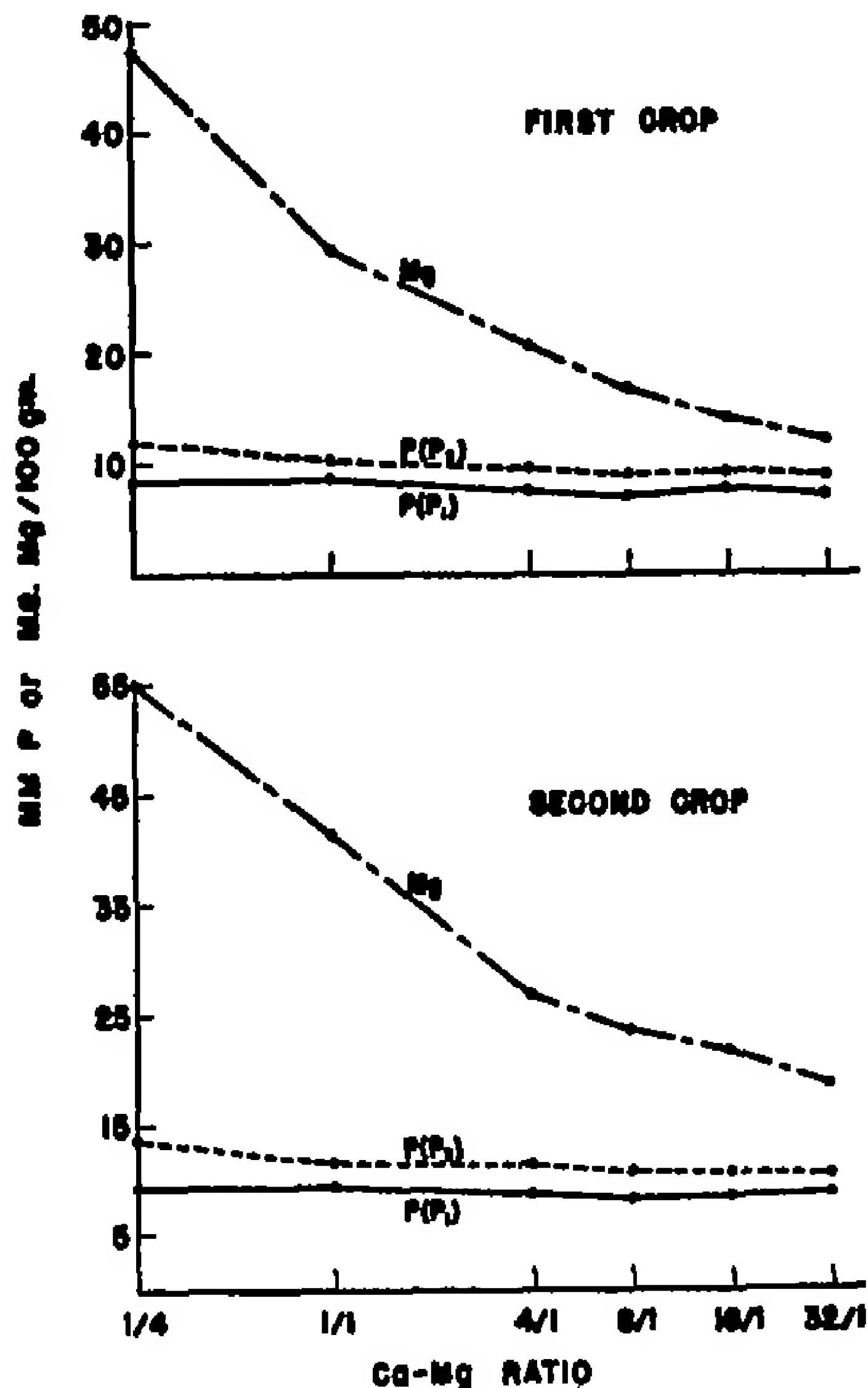


FIG 1 MILLIMOLES P AND MILLIEQUIVALENTS Mg PER 100 GM OF ALFALFA GROWN ON SOILS VARYING IN Ca/Mg RATIO AND P LEVEL

carbonate series produced plants having significantly higher percentage of N than those of the adsorbed series

*Percentage of lignin* The percentage of lignin was not affected by any of the variables studied. Lignin is indigestible by animals (5), and therefore the lignin content is one of the factors determining the nutritive value of forage crops such as alfalfa.

*Cation-equivalent constancy* The sum of milliequivalents of Ca, Mg, and K per 100 gm of alfalfa was calculated for each pot. In neither crop did the

Ca-Mg ratio have any significant effect upon the cation total. The data are in agreement with the observations of Bear and Prince (3) on the constancy of cations in alfalfa. Since the percentages of Ca, Mg, and K showed wide individual variation without effect upon alfalfa yield or upon the total cation content on the equivalent basis, it is evident that in the plant these elements perform some common functions.

#### *Comparison of methods of soil preparation*

As shown in tables 2, 3, and 4, in comparison with the carbonate series the soils of the adsorbed series produced the higher yield of alfalfa with the lower percentages of P and N, the higher percentages of Ca and K, and the higher total cation content. The only interaction of any significance between the method of soil preparation and either of the other two variables was the interaction with P level upon the yield of the first crop, it was significant only at odds of 19 to 1. The absence of other significant interaction effects of method of soil preparation with either P level or Ca-Mg ratio of the plants indicates that the same conclusions as regards the effects of these two factors upon mineral composition would have been reached had either method of soil preparation been used alone. Soils with given, known amounts of exchangeable ions may be prepared more simply and easily, and in much shorter time, by mixing carbonates and bicarbonates with H-soil than by first preparing humic soils and later mixing these.

#### SUMMARY AND CONCLUSIONS

A factorial pot study was made of the effect of variations in the exchangeable Ca-Mg ratio, the level of available P in the soil, and the method of soil preparation upon the growth of alfalfa and its content of P, Mg, Ca, K, N, and lignin. Two crops of alfalfa were grown.

The percentage of P in the plants was increased significantly as the Ca-Mg ratio decreased and the amount of available Mg was increased sufficiently to be equal to or greater than the amount of Ca, when Ca exceeded Mg, increasing Mg had little influence on the uptake of P. There was no direct relationship between the absorption of Mg and P, with decreasing Ca-Mg ratio, the increase in Mg content of the alfalfa was several times as great as the increase in P content. The level of available P in the soil was the most important factor affecting the P content of the alfalfa.

The weight of alfalfa produced was not affected by variations from 1/4 to 32/1 in the Ca-Mg ratio, these values represent ratios both higher and lower than are normally encountered in soils.

The percentages of Ca, Mg, and K varied over wide ranges with variations in the Ca-Mg ratio, but in each crop the sum of equivalents of the three cations was constant. The percentage of lignin was unaffected by any treatment variable.

The methods of preparing soils having given known amounts of exchangeable ions by mixing humic soils and by adding carbonates and bicarbonates to H-soil were compared in this study. The absence of significant

effects of interaction of method of soil preparation with either Ca-Mg ratio or P level indicates that the same conclusions as regards the effects of these two factors upon mineral composition would have been reached had either method been used alone. Preparation by the latter method is simpler and less time-consuming.

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# QUALITATIVE STUDIES OF SOIL MICROORGANISMS VIII INFLUENCE OF VARIOUS CROP PLANTS ON THE NUTRITIONAL GROUPS OF SOIL BACTERIA<sup>1</sup>

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The study of different physiological groups of soil bacteria has been concerned largely with observations on organisms developing on media selected to favor such groups. Mainly because of a lack of suitable methods, relatively little is known of a large proportion of the microorganisms indigenous to soil. In this series of investigations an attempt has been made to develop a more objective approach to the study of soil bacteria, in which emphasis is placed on the organisms themselves, isolated by nonselective methods and the functions of which are unknown, rather than on special groups of soil organisms associated with various known biochemical processes (7, 13)

Based upon the assumption that the relative abundance of soil microorganisms depends mainly upon availability of nutrients necessary for their growth, a method of grouping soil organisms has been proposed (9). This depends upon the determination of growth response in a series of media of increasing nutritional complexity. It is felt that the application of this method of study to an investigation of microorganisms of the rhizosphere, that is, the immediate zone of influence of the living plant root, might contribute to a better knowledge of the nature of root excretions and of factors related to crop rotation and the control of soil-borne diseases of crops (10).

Many previous investigations, beginning with the observations of Hiltner (3), have established the fact that soil in the rhizosphere contains higher numbers of microorganisms than soil not within the influence of the plant root. It has been shown also that in the rhizosphere the balance between certain physiological groups is changed (1, 5, 11, 12) as well as that between different morphological types of bacteria or fungi (6, 8, 14). Studies with respect to nutritional groups of soil bacteria have shown a preferential stimulation of certain of these groups in the rhizosphere soil as contrasted with soil not under the influence of the growing plant root (4, 10, 17).

The purpose of the present investigation was to compare different crop plants, studied at different growth stages, to note any specific rhizosphere effects which may be exerted in modifying the balance between different nutritional groups of soil bacteria.

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<sup>2</sup> Assistant bacteriologist and Dominion agricultural bacteriologist. The authors wish to thank C. H. Goulden, Dominion cerealist, for his valuable help and advice regarding the statistical treatment of the data, and Mrs. Frances Johnson for technical assistance throughout the project.

## MATERIALS AND METHODS

Six crops—wheat, oats, red clover, timothy, alfalfa, and flax—were greenhouse grown in soil obtained from a plot in a 4-year rotation system of oats, clover, timothy, and mangels, 15 tons of manure being applied to mangels. A series of pots with uncropped soil served as controls. Duplicate samples for analysis were removed at two periods of plant development, one at the seedling stage and the other at or near the flowering stage. To obtain the rhizosphere samples, several plants, varying with the crop, were carefully taken from the soil, the roots shaken briskly to remove as much of the adhering soil as possible and then placed in 100 ml of sterile water in weighed flasks. Sufficient roots were added to approximate the turbidity of the 1:100 dilution of the control sample. Appropriate dilutions of both control and rhizosphere samples were made and aliquots of the final dilutions were plated with soil extract agar (13). The roots were removed from the flasks in which the original suspensions were made, and the contents, as well as those with the control soil suspensions, were evaporated to dryness for the estimation of plate counts on a dry-weight basis, correction being made for the aliquots removed.

All plates were incubated at 25°C for 10 to 14 days. From the whole area of a plate on which the colonies were suitably dispersed or from a definite sector of a plate, all colonies were systematically picked off until approximately 100 had been removed, these were cultivated as stab cultures in soil extract semisolid agar (9) to serve as stock cultures for further study.

The differential media and methods of grouping described by Lochhead and Chase (9) were used for determining the nutritional requirements of the isolated organisms, accordingly, the various bacteria were divided into the following groups:

- Group I—Bacteria with simple requirements
- Group II—Bacteria requiring one or more amino acids
- Group III—Bacteria requiring growth factors
- Group IV—Bacteria requiring amino acids plus growth factors
- Group V—Bacteria requiring unidentified substances in yeast extract
- Group VI—Bacteria requiring unidentified substances in soil extract
- Group VII—Bacteria requiring unidentified substances in both yeast and soil extract

## GENERAL RHIZOSPHERE EFFECTS

Table 1 shows the total plate count for each sample as well as the percentage incidence of each nutritional group from the rhizospheres of the seedling and older plants respectively, compared with the corresponding groups of bacteria in the control soil. The percentage values were calculated from the total numbers of cultures obtained from the two replicates of each soil and rhizosphere sample.

The results indicate that for all the crop plants there is, in the rhizosphere, a larger proportion of bacteria with relatively simple nutritional requirements as compared with the control soil. This is shown by the preferential stimulation of organisms capable of maximum growth in the basal medium and of those



requiring ammo acids (groups I and II), and in the case of older plants, of those responding to growth factors (group III) On the other hand, bacteria requiring for maximum growth the more complex substances in yeast and soil extract, particularly groups VI and VII, are proportionately less abundant in the rhizosphere The rhizosphere effect on the relative incidence of organisms of group V, requiring yeast extract for maximum growth, varied with the age of the plant With the seedling plants this group was relatively decreased in the rhizosphere, with the exception of flax, whereas in the rhizosphere of older plants it showed a proportionate increase throughout

TABLE 1  
Plate counts and percentage incidences of nutritional groups for control soils and rhizosphere soils of various crop plants

			WHEAT		OATS		RED CLOVER		TIMOTHY		ALFALFA		FLAX	
			C*	Rh*	C	Rh	C	Rh	C	Rh	C	Rh	C	Rh
Seedling Plants														
Plate count	millions/gm.		123	583	230	2080	134	2226	194	888	134	825	199	1119
Group I—Basal medium	%		10.4	37.7	13.8	23.1	8.8	34.8	8.8	21.8	8.8	29.1	7.3	26.8
Group II—Amino acids	%		4.8	4.8	3.3	11.8	3.3	20.8	3.3	4.8	3.3	11.4	2.4	9.8
Group III—Growth factors	%		13.8	28.0	8.8	11.7	11.8	13.1	11.8	11.7	11.8	14.3	8.5	12.7
Group IV—Amino acids growth factors	%		8.8	3.0	1.5	0.0	9.3	9.3	9.3	8.8	9.3	10.3	7.3	5.3
Group V—Yeast extract	%		21.8	17.7	26.7	18.8	19.8	11.1	19.8	14.8	19.8	14.8	10.3	30.8
Group VI—Soil extract	%		31.3	19.8	23.0	17.9	37.3	8.8	37.3	29.0	37.3	15.4	29.8	12.1
Group VII—Yeast extract soil extract	%		17.8	3.4	24.4	7.8	13.7	3.3	13.7	9.8	13.7	4.8	37.8	4.1
Older Plants														
Plate count	millions/gm.		189	1228	189	1375	257	2373	257	837	257	2387	146	1891
Group I—Basal medium	%		7.3	30.3	7.3	26.0	3.4	31.1	3.4	10.8	3.4	21.7	4.3	23.8
Group II—Amino acids	%		3.4	13.3	3.4	23.4	0.0	11.7	8.0	4.8	0.0	13.3	4.3	9.4
Group III—Growth factors	%		8.8	16.7	8.8	10.9	1.8	13.3	1.8	16.4	1.8	14.0	0.8	21.3
Group IV—Amino acids, growth factors	%		7.3	4.3	7.3	5.1	1.8	13.3	1.8	3.1	1.8	3.1	3.8	3.3
Group V—Yeast extract	%		10.3	17.0	10.3	23.1	7.1	14.8	7.1	13.3	7.1	18.8	13.3	13.8
Group VI—Soil extract	%		28.0	7.8	28.0	5.1	43.0	13.1	43.0	34.9	43.0	14.7	23.0	16.8
Group VII—Yeast extract soil extract	%		37.8	4.3	37.8	7.9	43.0	13.3	43.0	17.3	43.0	12.4	39.3	8.3

\* C = Control, Rh = Rhizosphere.

SPECIFIC RHIZOSPHERE EFFECTS OF VARIOUS CROP PLANTS

To note whether specific rhizosphere effects are exerted by the different crop plants, an analysis of variance was calculated separately for each bacterial group The numbers of organisms per gram of dry soil representing the respective groups were calculated from the total plate count and the percentage incidences for each sample. These values were transferred to logarithms for use in the analysis of variance, in line with the recommendations of Cochran (2) The different sources of variation and their respective mean variances are shown in table 2. The soils-crop plants interaction (specific rhizosphere effect) indicates significant differences in rhizosphere effect between the crops with respect to bacterial



groups I, II, III, IV, and V. These differences may be judged from graphs of the data used for calculation of the respective variances. Figure 1 depicts, for each group affected, differences between the logarithms of the rhizosphere soil numbers and those of control soils.

On the basis of the greatest differences between the various crops, it appears that red clover and alfalfa have a higher rhizosphere effect than wheat, oats, and timothy with respect to group I bacteria. For group II organisms, the effects of the rhizospheres of red clover and alfalfa are different from those of wheat, timothy, and flax. For group III organisms the effects of red clover,

TABLE 2  
Values calculated from the analysis of variance for each nutritional group

SOURCE OF VARIATION	DEGREES OF FREEDOM	MEAN VARIANCES						
		Group I	Group II	Group III	Group IV	Group V	Group VI	Group VII
Age of plants	1	0.06	0.14	0.07	0.00	0.01	0.09	2.46
Soils (control and rhizosphere)	1	31.15	31.15	19.89	10.14	11.66	8.77	1.67
Crop plants	5	0.29	0.32	0.13	0.50	0.19	0.39	0.28
Age of plants—soils	1	0.03	0.29	1.09	0.10	0.41	0.01	0.01
Age of plants—crop plants	5	0.11	0.11	0.12	0.52	0.10	0.25	0.40
Soils—crop plants (specific rhizosphere effect)	5	0.24*	0.37**	0.29**	0.34**	0.17**	0.06	0.07
Age of plants—soils—crop plants (effect of age)	5	0.09	0.25**	0.41**	0.16*	0.04	0.23*	0.03**
Error	24	0.07	0.04	0.02	0.05	0.03	0.06	0.03
Total	47	36.64	37.81	25.90	18.89	15.31	9.99	10.15

\* = Significant  
\*\* = Highly significant

alfalfa, and flax differ from those of wheat and oats. In bacterial group IV, the rhizosphere of red clover is different from those of all the other plants with the possible exception of alfalfa. In Group V, the effects of red clover, alfalfa, and flax are significantly greater than those of wheat, oats, and timothy. In general, the legume crops show a greater effect than the cereals and timothy, but only in two groups do they appear to have a different effect from that of flax.

RHIZOSPHERE EFFECT IN RELATION TO AGE OF PLANT

Calculations with respect to the age of plants-soils-crops interaction (age-rhizosphere effect) indicate that the age of certain crops significantly alters the bacterial population representing groups II, III, IV, VI, and VII. Figure 2 shows graphically the rhizosphere and control relationships of seedling plants compared with those of older plants. During the growth of wheat and alfalfa the rhizosphere effects appear to increase significantly with respect to group II

organisms. Likewise, the effects of alfalfa and flax increase for group III bacteria. In group IV organisms, increases are apparent with respect to the rhizosphere effects of red clover and flax, whereas that of wheat seems to have decreased. For group VI bacteria, the influence of the older wheat rhizosphere is greater than that of the seedling plant, whereas the reverse appears to be true for timothy. Finally, the effects of the older red clover and timothy rhu-

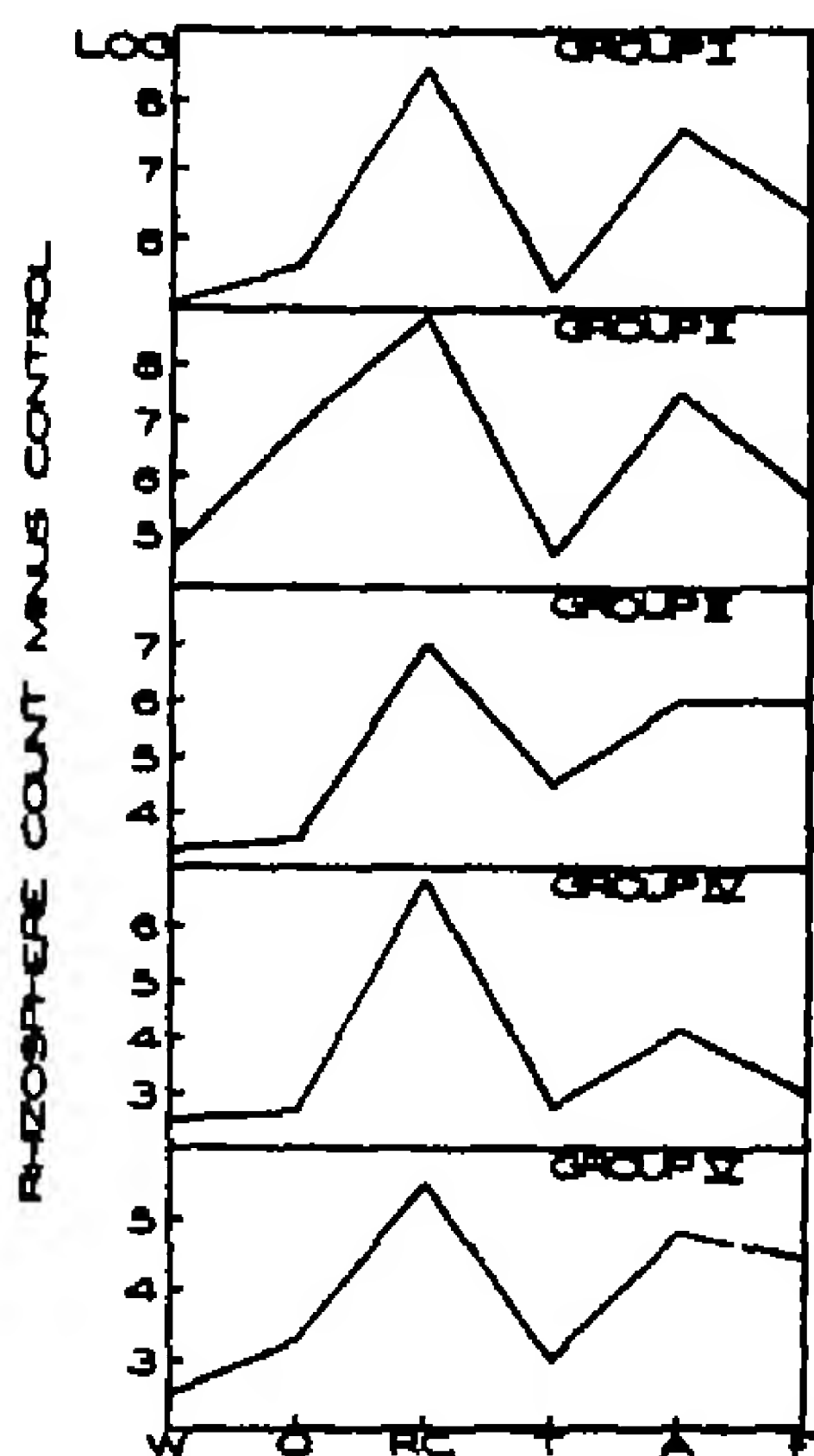


FIG 1

FIG 1 SPECIFIC RHIZOSPHERE EFFECT OF VARIOUS CROP PLANTS ON NUMBERS OF DIFFERENT NUTRITIONAL GROUPS OF BACTERIA

W = wheat, O = oats, RC = red clover, T = timothy, A = alfalfa, F = flax

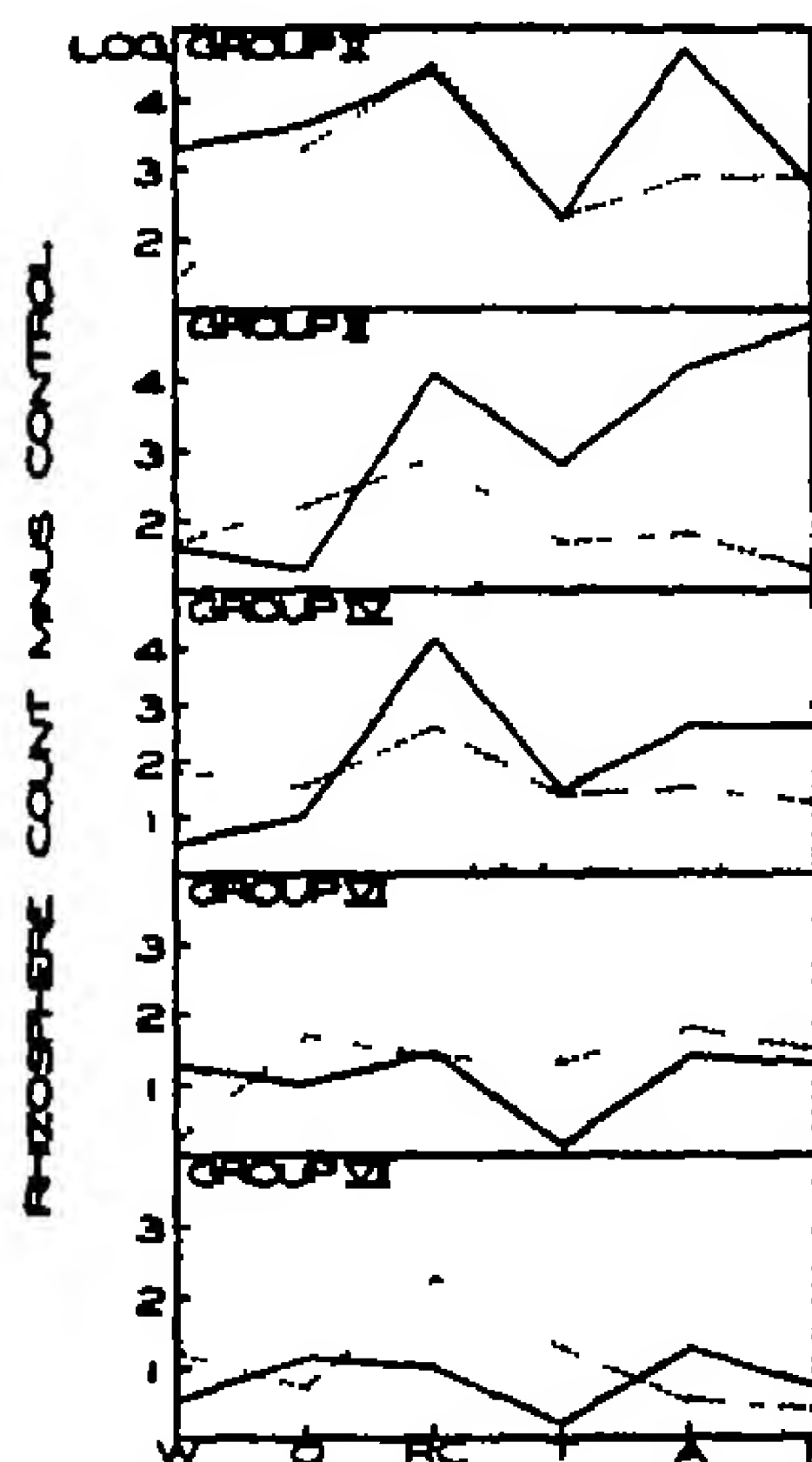


FIG 2

FIG 2 RHIZOSPHERE EFFECT IN RELATION TO AGE OF VARIOUS CROP PLANTS

W = wheat, O = oats, RC = red clover, T = timothy, A = alfalfa, F = flax. Solid line = older plants, broken line = seedling plants.

spheres appear to be significantly diminished with respect to group VII organisms.

#### DISCUSSION

In soil there is increasing evidence of a microbiological equilibrium, though one which is always subject to change through the influences of season, temperature, moisture, soil treatment, and cropping. Of these factors, which affect not only the numbers but also the balance between different groups of soil bacteria, the growing plant appears to have the greatest effect under normal conditions. Previous studies on the influence of the growing plant on soil bacteria, by use of

the quantitative-qualitative approach on a nonselective basis, have indicated a rhizosphere effect characteristic of all plants studied. In the zone of influence of the root there has been noted a qualitative change in the bacterial flora, shown by a shifting of the balance between different groups of organisms, whether these are classified on the basis of morphology, general physiological activity, or, by what is believed to be a more rational grouping, according to their nutritional requirements.

Though different crop plants conform to a general pattern in their rhizosphere effect on soil bacteria, results of the present study point to specific effects exerted by different crops in modifying the microbial balance in soil. Thus legumes, particularly, appear to exert a more pronounced effect in stimulating significantly bacteria of groups I, II, and, in the case of red clover, group IV. Since groups II and IV both require amino acids, this finding is of interest in connection with the demonstration of amino acid excretion by leguminous plants (15). A further point of interest is the effect of flax which, together with the two legumes, has a more pronounced influence than wheat, oats, or timothy on organisms of groups III and V, requiring respectively known growth factors or those contained in yeast extract. This finding supports indirectly the work of West (16) respecting the excretion of thiamin and biotin by the roots of flax seedlings.

It is recognised that the preferential stimulation of certain microbial groups in the rhizosphere cannot necessarily be attributed to the effect of root excretion alone, but that decomposition products of sloughed-off epidermal cells and root hairs must be considered. Since fewer significant differences in rhizosphere effects were noted, however, between seedling and older plants than between the crops themselves, the results suggest that the changes in the microbial balance in the rhizosphere cannot be ascribed solely to the breakdown of sloughed-off material, and that root excretion must be considered as an important factor.

The indication that different crop plants exert specific effects on the bacterial flora, by which the qualitative nature of the organisms in the environment of the growing plant is altered, points to the value of further work to elucidate more fully such specific influences. This not only will contribute to a greater knowledge of root physiology, but should aid in a better understanding of the fundamentals underlying the principles of crop sequence and related questions of plant growth, as well as plant disease problems related to soil conditions.

#### SUMMARY

Bacteria isolated from the rhizospheres of wheat, oats, red clover, timothy, alfalfa, and flax, as well as from uncropped soils, were grouped according to their nutritional requirements.

A general rhizosphere effect shown by all crops at two stages of growth was indicated by a much higher percentage, in the rhizosphere, of bacteria with the simplest nutritional requirements than in soil without crops. The situation was reversed with regard to bacteria requiring the complex nutrients of soil extract.

Significant differences in rhizosphere effect between certain crops were noted for bacteria giving maximum growth response in a glucose-inorganic-salts medium and in that medium supplemented with amino acids, growth factors, amino acids

and growth factors, and yeast extract respectively. In the main, these specific differences existed between red clover, alfalfa, and flax on the one hand and wheat, oats, and timothy on the other. The legumes, however, differed from flax with respect to bacteria responding to amino acids and amino acids plus growth factors.

Significant differences were found in the rhizosphere effect on five of the bacterial groups between plants at the seedling and flowering stages, but such differences were limited, in the case of each group, to one or two crops.

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## BOOKS

*Origin and Regime of Saline Soils* By V. A. KOVDA Dokuchaev Soil Institute of the Academy of Science of the USSR, Moscow-Leningrad, 1946 Pp 568 [In Russian]

This is the first of two volumes of a treatise on saline soils. It is based largely on the author's recent investigations at the two Experimental Stations in Russian Central Asia, in the Fergana Valley and the Golodnaya (Hungry) Steppe.

The book is divided into three parts, the first of which deals with the general principles of migration and accumulation of salts, the second with salinization of ground water, soil solutions, and soils and parent materials, and the third with the hydrologic and salinity regimes of saline soils. The author differentiates between the total content of soluble salts in the soil and the salt content in the soil solution and emphasizes the significance of the ratio of salt content in the solid to that in the liquid phase of the soil.

Kovda states that "salinity of ground water even in the most strongly salinized soils seldom exceeds 100 or 150 gm per liter. Apparently some powerful factors preclude further concentration of salts in ground water beyond these limits." Concentration of salts in the soil solution may reach 300-400 gm per liter. The increase of salinity of the soil solution, as compared with that of ground water, is due largely to the higher temperature of the upper soil horizons. The content of the different salts in the soil solution varies with the concentration of such a solution. With an increase in concentration the least soluble compounds, such as iron oxides, silica, and lime, begin to precipitate, then the progressively more soluble, gypsum,  $\text{Na}_2\text{SO}_4$ , and  $\text{MgSO}_4$ . Precipitation of such salts as  $\text{NaCl}$  takes place only from solutions the salt content of which reaches 300-350 gm per liter. Sesquioxides, silica, and lime follow the gypsum precipitate in the deeper soil horizons, whereas salts such as  $\text{NaCl}$ ,  $\text{MgSO}_4$ , and even  $\text{Na}_2\text{SO}_4$  may be carried to the very surface of the soil. Precipitation of lime and gypsum, and to a certain extent  $\text{Na}_2\text{SO}_4$ , is virtually irreversible, whereas salts like  $\text{NaCl}$  and  $\text{MgCl}_2$  may precipitate in dry seasons and pass into solution again during the rainy periods. Thus, there is a tendency for a fixed accumulation, in various soil horizons, of the sesquioxides, silica,  $\text{CaMg}(\text{CO}_3)_2$ ,  $\text{CaCO}_3$ , and  $\text{CaSO}_4$ , and concentration of  $\text{NaCl}$ ,  $\text{MgCl}_2$ ,  $\text{MgSO}_4$ , and some  $\text{Na}_2\text{SO}_4$  in the soil solutions and ground water. Accumulations of lime and gypsum individually or in combinations with the sesquioxides and silica may lead to development of hardpans.

Kovda differentiates four types of salinization of soils on the basis of the most conspicuous salts—salinization by carbonates (soda) and sulfates, by sulfates with some chlorides, by chlorides with lesser amounts of sulfates, and overwhelmingly by chlorides. These represent the segments of a continuous series in which the relative content and importance of chlorides gradually increase until the effects of their presence in the soil dominate those of other salts. The soda-sulfate salinization is typical of the relatively temperate subarid climate, the



chloride salinization, of the most arid and hot climate, whereas the other two types, sulfate-chloride and chloride-sulfate take place under intermediate conditions. These four types of salinization represent not merely the differences in the character of saline soils in various climatic regions but also the evolutionary stages of a progressive salinization of the area which begins with the salinization by carbonates and sulfates and progresses toward the highest state of chloride salinization. Such an evolution of salinity is determined by the changes in climate toward an increasing aridity with an enhancement of the effectiveness of evaporation.

The author tacitly postulates a possibility of formation of various salts in any soil which is liable to salinization if the hydrologic regime of such a soil does not provide for some means of removal of these salts as fast as they can form. "Certain geomorphic and topographic conditions which provide for a high groundwater table and predominance of evaporation over leaching are essential for the effectiveness of aridity and continentality of the climate in the development of salinization." Salinization is typical of the accumulative provinces in broad arid basins and basinlike depressions. As regards the macrorelief and the mesorelief, a conspicuous accumulation of salts is associated with the most depressed areas. Within such areas the salts tend to concentrate on relatively elevated spots which are subject to much faster desiccation than the adjacent depressions.

C. C. NIKIFOROFF

*Annual Review of Biochemistry* Volume XVII Edited by J. MURRAY LUCK  
Annual Reviews, Inc., Stanford, California, 1948 Pp 801 Price \$6

The preface of this volume reports that, in 1934, some 750,000 scientific papers were published in 15,000 scientific periodicals, which were selected as the most useful of the 36,000 in a more complete list. It is believed that the number now is considerably larger. This provides material for thought and abundantly justifies the publication of annual reviews of the type here reviewed. In this volume, 27 subjects are considered, including oxidations, reductions, enzymes, x-ray studies, hormones, vitamins, carcinogenesis, pigments, terpenes, alkaloids, photosynthesis, bacterial metabolism, ruminant digestion, physiological aspects of genetics, chemistry of carbohydrates, immunopolysaccharides, lipids, proteins and amino acids, nucleoproteins and nucleic acids, and penicillin, and metabolism of carbohydrates, lipids, proteins and amino acids, and drugs and toxic substances. Of special interest to those concerned with soil-plant relationships is the chapter on mineral nutrition of plants, by H. Burström, University of Lund, Sweden. The references, long lists of which are appended to the several chapters, total over 4,000, and comprise the publications of some 4,500 authors. This volume is an excellent addition to those previously published.

*Bacterial Chemistry and Physiology* By JOHN ROGER PORTER John Wiley and Sons, Inc., New York, 1946 Pp 1073 Price \$12

Developments in microbiological science have been so rapid within recent years that it is difficult to keep as well informed about them as one would like. The



author endeavors to bring the subject of bacterial chemistry and physiology up to date, at least as of the day when the book was completed. The material is presented in 10 chapters dealing with physicochemical properties of bacteria, growth and death, effects of physical agents, effects of chemical agents, chemical composition, enzymes and respiration, nutrition, metabolism of carbon compounds, metabolism of nitrogen compounds, and microbial fermentations. The chapters on bacterial composition, nutrition, and metabolism are of special interest to workers in soil-plant science. A list of references is appended to each chapter, the total number for the entire book being over 3,000. The author is entitled to the thanks of the workers in this field, and in the many closely related fields, for the preparation of such a comprehensive and careful review of the subject.

*Biochemie der Spurenelemente* By KARL SCHARRER. Edwards Brothers, Inc., Ann Arbor, Michigan, 1943. Pp 272, Price \$7.55.

This is a photo-lithoprint reproduction published by authority of the Alien Property Custodian. It contains excellent summaries of the research on 33 elements. These include all the commonly mentioned trace elements that are known to have favorable or unfavorable effects on plants and animals, and many others as well. Appended is a very comprehensive bibliography, which contains references to some 2,500 scientific papers. About 60 per cent of these references deal with boron, copper, manganese, and zinc. The introductory statement, the over-all picture of the problem, and the reviews of the individual elements give a very comprehensive and detailed picture of the present status of research in this field and make the book a highly important addition to the literature.

*Crop Management and Soil Conservation*. Second Edition. By JOSEPH F. COX AND LYMAN E. JACKSON. John Wiley and Sons, Inc., New York, 1948. Pp 572. Price \$3.80.

This book is dedicated "to the future farmers of America, in whose keeping largely rests the future of our country." It is written primarily for use in teaching students in vocational agriculture. The first half of the book deals with the over-all problems of soil and crop management. The last 16 chapters take up individual crops or groups of crops for special consideration. Appended to each chapter are a set of teaching suggestions and several references for supplemental reading. The book is well illustrated, and the material is attractively presented. Many farmers would probably find it very good winter reading.

*Instrumental Methods of Analyses*. By HOBART H. WILLARD, LYNNE L. MERRITT, JR., AND JOHN A. DEAN. D. Van Nostrand Company, Inc., New York, 1948. Pp 247. Price \$4.

This is a paper-bound, 8½- by 11-inch volume which is an outgrowth of the lectures and laboratory work in instrumental analysis given at the Universities of Michigan and Indiana. The purpose is to acquaint the student with the various types of instruments that are available, the theories involved in their

manufacture, and their advantages, disadvantages, and limitations. The 17 chapters cover fundamental laws of colorimetry, photoelectric colorimeters, fluorescent meters, turbidimeters, nephelometers, spectrophotometers, flame photometers, spectrographs, x-ray diffraction, radioactivity, refractometers, interferometers, thermal conductivity, mass spectrometry, centrifuges, pH determinations, potentiometric titrations, conductometric titrations, electrolytic separations of metals, polarographs, and amperometric titrations. The appendix contains some very useful tables of potentials, constants, definitions, and common logarithms. The material is well presented and documented. The illustrations are excellent. Every modernized chemical laboratory should have a copy of this book.

*Maintenance of Shade and Ornamental Trees* Second Edition By P. P. PIRONE  
Oxford University Press, New York, 1948 Pp 436, figs. 173

This corrected and enlarged edition contains all the material in the first edition (reviewed in SOIL SCIENCE 52:84, July, 1941) plus an appendix describing the more important new insecticides, fungicides, and spraying machinery and giving up-to-date information on new diseases and insect pests and their control. A selected bibliography of publications of the last 7 years has also been added, and new photographs have been substituted for several of those in the earlier edition. Some of the illustrations have suffered in the reprinting, a few have been improved. Those who own or care for shade trees will find the latest edition of this authoritative book invaluable.

*Marching with the Grasses* By RAYMOND J. POOL University of Nebraska Press, Lincoln, 1948 Pp 210, figs. 84 Price \$3.50

The author of this book develops the thought that the wild and cultivated grasses have played a highly important part in the slow evolution of human society. When one considers that he is dealing with wheat, rice, corn, barley, oats, rye, sorghum, millet, and sugar cane, with the great natural grassland areas of the world, with the grasses that cover the ranges and are used for pasture and meadow, and with the use of grasses in soil conservation and for lawns, parks, and playing fields, one is inclined to agree with this concept. The beginning chapter gives the family traits of the grasses, and the last chapter, a number of miscellaneous interests in grasses, of which the straw hat is an example. A list of some 250 references is appended. Some very instructive world maps, showing the centers of location of some of the more important of the grass crops, are contained in the book. The author is to be congratulated on having written not only a very useful book, but one that makes very interesting reading and that stimulates thinking on this highly important subject.

*New Riches from the Soil* By WHEELER McMILLEN D. Van Nostrand Company, Inc., New York, 1946 Pp 397 Price \$3.50

This is a report of the activities of the National Farm Chemurgic Council by the president of that organization and the man who is primarily responsible for

its concepts and accomplishments. It deals with the possibilities of finding new uses for old crops, redesigning current crops to fit specific needs, introducing crops from other parts of the world, and developing new crops from weeds and other wild plants. The author has succeeded in getting a great many very important scientists and laymen interested in this work, and their thoughts on these matters and their activities in relation thereto, as told in this book, make highly interesting and stimulating reading. The record of the achievements of this agency is impressive. It would be a good thing if every man who has to do with determining the agricultural policies for his state and nation would read the book.

*Road to Survival* By WILLIAM VOGT William Sloane Associates, Inc., New York, 1948 Pp 335, figs 8 Price \$4

The writer of this book endeavors to deal with the problems arising from man's conquest of the earth. He considers our natural resources, their exploitation by mankind, the growth of populations, and the possible consequences if controls do not become operative. He points out that the curves of population and of the means of survival have crossed and are ever more rapidly drawing apart. He argues that the first step toward a solution is world-wide education. The second step is control of populations and the husbanding of our resources. The final sentence gives the essence of his philosophy. Unless we take these steps, he says, "Like Gadarene swine, we shall rush down a war-torn slope to a barbarian existence in the blackened rubble." The introduction is by Bernard Baruch. Well-developed lists of references are given in the appendix, chapter by chapter, and also a supplemental reading list. The material is lucidly presented and highly impressive. It is to be hoped that the book enjoys a wide reading.

THE EDITORS



## SOIL CLASSIFICATION

This special issue of SOIL SCIENCE was arranged for at our suggestion by a committee of American soil scientists deeply interested in soil classification. The organizing committee consisted of the following members:

Marlin G. Cline, Cornell University  
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Roger P. Humbert, Saratoga Laboratories, Saratoga Springs, New York  
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THE EDITORS

## INTRODUCTION

CHARLES E. KELLOGG<sup>1</sup>

The authors of this symposium have attempted to present the current theory basic to the American system of soil classification. Within these few pages, only principles may be dealt with, neither soil descriptions nor historical reviews.

The reader may note inconsistencies among the papers. One can say only that truth has many facets, some of which, and their connections, are still obscure. Nor is modern theory wholly consistent with the published work. The system of soil classification developing over the last half century in the United States has reflected fundamental changes in theory and great improvements in technique. Inconsistencies may still be found in the system. As research goes forward, more changes will be needed as we come closer to the truth. In fact, this symposium was prepared in the very midst of renewed research on tropical soils and the revision of their definitions and nomenclature. But any summary of principles in an active field of research is bound to be out of date in some respects when written. The only alternative is to have no summaries at all.

## SOILS AS INDIVIDUALS

Soil is the natural medium for the growth of land plants. In various forms, soil in this sense covers the earth as a continuous sheet from pole to pole. Its characteristics in any place result from the five genetic factors—climate, living matter, relief, parent rock, and time—plus the effects of man's use. Similarly, rock, living matter, and other natural things exist as continua in nature.

In both research and practice, one does not deal with the whole continuum at

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once. Individuals must be recognized. If we make any use of experience and science, classification becomes a necessity. Scientists deal with plants, not with vegetation as a whole. Similarly, instead of soil, we have soils. Thousands of unique kinds of soils exist in the world, in fact, as many kinds as there are significant combinations of the five genetic factors. Then beyond the natural soils are those produced by use through modification of the natural ones.

In this second sense, as an individual in the continuum, a soil is a dynamic three-dimensional piece of landscape that supports plants. It has a unique combination of internal and external characteristics with definable ranges of expression. Its upper surface is the surface of the land, its lower surface is defined by the lower limits of biological forces, and its sides are boundaries with other kinds of soil where there is a change in one or more differentiating characteristics. Through research, its behavior under defined conditions can be predicted.

The characteristics of each soil are learned through observation and research in the field and laboratory. A soil is a combination of characteristics resulting from a combination of genetic factors. Its future potentialities as well as its previous history are contained in these characteristics. The influence of any one characteristic, or the significance of a variation in any one, depends upon the others in the combination. Thus, a general system of soil classification comprehends all observable characteristics, not merely a selected few.

To understand the relevance of a particular soil characteristic or of an individual genetic factor, sets of soil characteristics must be compared. These sets are the units in soil classification. The place of an unknown soil in the system of classification, or the relationship of such a soil to other units in the system, is determined by comparing the set of characteristics of the unknown soil with those of the known soils in the system. Such scientific correlation is the central core of soil classification.

#### SCIENTIFIC METHODS

Soil science may be classified with the physical sciences, the biological sciences, or the earth sciences. It is not any one, it is all three. It uses principles and methods from all three in addition to those which are peculiar to itself. That is, a large body of fundamental scientific subject matter exists in soil science that is the concern of no other discipline.

Commonly, in chemistry and biology, scientists depend largely upon one general scientific method—the experimental method. Unconsciously, some persons have even assumed that the experimental method is the only method in science. Since simple observations often fail to tell us much about causes or results, the scientist sets up experiments in which he can control, or at least account for, the effects of variables besides the particular one under study. This method is used widely in soil science. Through the experimental method, we discover the specific effects of variations in individual<sup>1</sup> soil characteristics, and groups of characteristics, under defined conditions. But such research, at best,



deals only with samples of real soil, perhaps in the laboratory, in the greenhouse, or in the experimental plot. Of course, one cannot bring a soil into the laboratory any more than one can bring in a mountain, or a river, or a glacier.

Yet a great many matters must come under scientific study that cannot be subjected to experiment. One gets at the relative influences of two climatic regimes in the formation of soil from granite through use of the experimental method and the method of correlation. The experimental method deals with soils at points. To interpret the results for an understanding of real soils, or for predictions about their functioning, these must be synthesized in terms of soils as defined, three-dimensional landscapes. This is the function of soil classification. Its stuff comes from observation and the experimental method. Its working tool is the method of logical scientific correlation.

#### GEOGRAPHIC PREDICTION

Principles of prediction value come, in part, by inductive reasoning from data obtained through rigidly controlled laboratory and greenhouse experiments on soil samples. But soil science is still so young—young in relationship to the enormous size and complexity of its universe—that chief reliance for principles of prediction value must still be placed on data obtained on known soils through natural field experiments, controlled field experiments, and the analysis of experience.

Thus, principles of prediction value emerge from intimately coordinated research using the experimental method and the method of scientific correlation. Exclusive reliance on either method gives little of value to fundamental or to applied soil science. Soil classification is essential for synthesis and coordination of the results.

Then beyond the strictly scientific process, if the results are to be applied, there must be some means of recognizing the individual units of the classification in the field. Only a very tiny fraction, at best, of the people using the principles of soil science will themselves be able to identify the units. It is essential to have soil maps. With the soil units shown accurately on maps and named in a standard system, predictions developed through research are available for application. Yet besides this immediate need for soil mapping, a system of soil classification is essential for remembering characteristics, for understanding relationships, and for developing principles in the whole broad field of soil science.

Thus, the system of soil classification is exposed to continuous scrutiny, both from the theoretical side as a natural system and from the practical side as a basis for predicting the outcome of management practices. The more important the work has become—the more it has been used—the greater the body of criticism. This has been good. Rather than indicating serious difficulty, criticism indicates growing use and importance. Without it, the great progress of the last few years would not have been made.

Finally, the goal of applied soil science implies accurate soil maps of all lands with classificational units appropriately defined in terms of all relevant data.



bearing on the potentialities of these lands for use. Then each farmer, gardener, forester, or rancher can design his management system on predictions based upon all experience of other land users and all results of scientific research on soils like his.

The more nearly we approach this far-distant goal, the more optimistic we may become over the prospect for production of abundant food, fiber, and timber on a secure basis for both soil and people.

## BASIC PRINCIPLES OF SOIL CLASSIFICATION

MARLIN G. CLINE<sup>1</sup>

The purpose of any classification is so to organize our knowledge that the properties of objects may be remembered and their relationships may be understood most easily *for a specific objective*. The process involves formation of classes by grouping the objects on the basis of their common properties. In any system of classification, groups about which the greatest number, most precise, and most important statements can be made *for the objective* serve the purpose best. As the things important for one objective are seldom important for another, a single system will rarely serve two objectives equally well.

### CLASSES

The smallest natural body that can be defined as a thing complete in itself is an *individual*. All the individuals of a natural phenomenon, collectively, are a *population*. Plants, animals, or soils, for example, are populations, each consisting of many individuals. The individuals of a population have many common properties, but the variation within a population is so great that man is unable to see similarities and understand relationships among individuals in the disorderly arrangement in which he finds them. He attempts to make the variation that he finds in nature orderly for his convenience by framing classes—by grouping individuals that are alike in selected characteristics. A *class* is a group of individuals, or of other classes, similar in selected properties and distinguished from all other classes of the same population by differences in these properties.

#### *Classes as segments of a population*

There is diversity in the degree of difference among classes. Among living things, for example, plants as a class are so unlike animals as a class that one thinks of them as separated by an insurmountable barrier of differences. Amoebae as a class and algae as a class are not so different, yet one is an animal and the other a plant. Similar situations may be found within every population. If one could place all the individuals in a row ranked from highest to lowest value of one property, the series formed would pass by almost imperceptible stages from one extreme of the property to the other. Any two adjacent individuals would be much alike, the two end members would be vastly different. Classes based on that property would be segments of a continuous series. The end individual of one class would be more like the adjacent end member of the next class than like an individual at the other extreme of the same class. Classes of natural objects are not separated by insurmountable barriers, they grade by small steps into other classes.

#### *The modal individual*

Within every class is a central core or nucleus to which the individual members are related in varying degrees. The mean, the median, and the mode as used in

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statistics, for example, are estimates of the central nucleus of a class. A class of natural objects may be considered in terms of a frequency distribution according to value of a selected property. Commonly, within some small increment of value of that property, the frequency of occurrence of individuals is a maximum. This is the modal value of the property which defines the central nucleus of the class—the modal individual. The definition of the modal individual may be based on observed properties of a real individual, or it may be estimated by a statistic representing a hypothetical individual and derived from the observed properties of a sample of the class.

One may visualize a class as a group of individuals tied by bonds of varying strength to a central nucleus. At the center is the modal individual in which the modal properties of the class are typified. In the immediate vicinity are many individuals held by bonds of similarity so strong that no doubt can exist as to their relationship. At the margins of the group, however, are many individuals less strongly held by resemblance but more strongly held by similarity to this modal individual than to that of any other class. A class is a group of individuals bound from within, not circumscribed from without. The test of proper placement of any marginal individual is its relative degree of similarity to the modal individuals of different classes.

#### *Characteristics of classes*

So far, variation in only a single property has been considered, but the same concepts and principles apply when two or more characteristics vary at the same time. Their application, however, depends upon an understanding of the different kinds of characteristics of classes.

Some property must be chosen as the basis of grouping. Individuals that are alike in that characteristic are placed in the same group, those that are unlike are placed in different groups. The property chosen as the basis of grouping is called the *differentiating characteristic*.<sup>2</sup> It serves to differentiate among classes, its mean value within each class defines the modal individual of that group. The test of any grouping is the number, precision, and importance of statements that can be made about each class for the objective. If the classes are well formed, a precise statement about the differentiating characteristic for each class should always be possible.

If the basis of grouping is good, the differentiating characteristic should be associated with a number of covarying properties. Texture, for example, is the differentiating characteristic of soil types within a soil series. A number of other properties, such as cation-exchange capacity of the inorganic fraction and water held at various tensions, change as texture changes. A precise statement can be made about these *accessory characteristics* as well as about texture in the soil type. Through accessory characteristics one multiplies the number of statements about each class and increases the significance of the classes formed. A

<sup>2</sup> The term is used here in a less restricted sense than that defined by Mill (5). As Mill used the term, it applied only to distinctions used to differentiate between greatly contrasting populations, such as plants and animals.

well-conceived grouping is based upon that differentiating characteristic that (a) is itself important for the objective and (b) carries the greatest possible number of covarying accessory characteristics that are also important for the objective

Those properties of the individuals of a class that vary independently of the basis of grouping are called *accidental characteristics*. They are not related to the differentiating characteristic, and no statement can be made about them for the class as a whole. Slope, for example, may vary independently of soil texture and is an accidental characteristic in classes based on texture.

Now consider the concept of a class as a group the members of which are ranged about a modal individual when many properties are variables. The modal individual may be defined precisely not only in terms of a value of the differentiating characteristic but also in terms of values of all its accessory characteristics. The class as a whole can be defined precisely in terms of (a) values both of the differentiating and of the accessory characteristics of the modal individual and (b) the respective deviations from those values within the range of the class. These should be the components of precise definition of classes. The

TAB E 1  
*A simple two-category system of classification of surface soils*

CATEGORY	DIFFERENTIATING CHARACTERISTIC	CLASSES			
		Light		Dark	
2	Color value				
1	Reaction	Acid	Alkaline	Acid	Alkaline

mean values for both differentiating and accessory characteristics derived from a sample of the class define the modal individual. Their standard deviations define the variability of the class. The tests of statistical significance are measures of whether the differences between classes are real or only apparent.

Accessory characteristics grade into properties that are purely accidental. Some attributes are almost always accessory but in a few individuals bear no relationship to the differentiating characteristic. The dark color of the A<sub>1</sub> horizon of soils, for example, is usually associated with high organic matter, but in the "Regur" soils of the tropics it is not. Such properties cannot properly be specified in the definition of a class, but they can and should be described.

MULTIPLE CATEGORY SYSTEMS

When a population is so diverse that any single grouping fails to show the relationships desired, the classes formed may be subdivided to show more relationships. This is illustrated in table 1. A *category* in such a system is a series of classes, collectively, formed by differentiation within a population on the basis of a single set of criteria. A category must include all individuals of the population, groups within a category are classes at a defined *level of abstraction*. Classes of category 2 in table 1 consist of groups of classes of category 1. Both include all individuals of the population. The technical meaning of the term *category* in classification is not to be confused with its common use as synonymous with *class*.

### *Categorical rank and homogeneity of classes*

The number of statements about classes in a multiple-category system increases in going from higher to lower categories. In table 1, the classes of category 2 are differentiated on the basis of color values. Statements about either of the two classes are limited to color and associated accessory characteristics. Reaction is purely an accidental characteristic in this category, and no statement can be made about it. This category by itself is a simple single-category classification. In category 1, however, each class of category 2 is subdivided on the basis of reaction. Each of these four classes may be defined in terms of (a) the differentiating and accessory characteristics of category 2, *plus* (b) the differentiating property of category 1, and all of its accessory characteristics. In any multiple-category system, regardless of the number of categories, the properties that are homogeneous in a given class consist of the accumulated differentiating and accessory characteristics of that category and all categories above it. The greatest number of statements can be made about classes of the lowest category, the least number of statements, about units of the highest category. Categories in which few differentiating and accessory characteristics have accumulated are at a high level of abstraction and have high categorical rank, those in which many have accumulated are at a low level of abstraction and have low categorical rank. Homogeneity of classes increases with decrease of abstraction and categorical rank.

### *Dependence of classification systems on state of knowledge*

When viewed in the opposite perspective, each successively higher category is a grouping of classes of the preceding lower category. Classes of a lower category are treated as individuals and grouped into classes of a higher category to show relationships among them.

The units of a lower category are not groups formed by applying a single differentiating characteristic to the entire population. They are homogeneous with respect not only to the differentiating property of that category but also to all characteristics used to differentiate in all higher categories. Formation of classes at a low categorical level in their final form, therefore, presupposes knowledge of the population adequate to complete all categories above it. *As the body of knowledge about any phenomenon increases, therefore, attempts to effect a complete natural system of classification must pass through a series of approximations.* The degree of improvement of each over its predecessor is in proportion to the increment of accumulated knowledge and its effects in basic concepts.

### NATURAL AND TECHNICAL SYSTEMS

Although there are as many "best" systems of classification as there are objectives for grouping, not all are equally significant in organizing man's knowledge. The lowest category of the natural classification is a prerequisite of all other groupings.

In a natural classification, one classifies in such a way that the name of each class will bring to mind many characteristics and will fix each group mentally in relation to all others. The objective is to show relationships in the greatest

number and most important properties. In the process, however, one gathers into classes of the lowest category the multitude of individual objects which are impossible of separate investigation by reason of sheer numbers. It has been shown that these classes are homogeneous with respect to the accumulated differentiating and accessory characteristics of all categories of the system. They are homogeneous within the limits of existing knowledge about the properties of the population and about the significance of differences within it. The natural classification, therefore, performs the extremely important function of organizing, naming, and defining the classes that are the basic units used (a) to identify the sample individuals that are the objects of research, (b) to organize the data of research for discovering relationships within the population, (c) to formulate generalizations about the population from these relationships, and (d) to apply these generalizations to specific cases that have not been studied directly. No other grouping provides such units, it is this fact that sets the natural classification apart from all other groupings.

Given the classes of the lowest category of the natural classification, one can group them for a great variety of technical purposes, as illustrated by Orvedal and Edwards (6). One may group soil classes of the lowest category, for example, to select a sample representative of specified soil conditions for research on phosphorus fixation, to discover genetic relationships, or to apply engineering principles in highway construction. These are *technical groupings*, each for a limited objective, each with a special bias dictated by the objective. Each must be based on those few properties that are most significant for the objective. Although only a few properties need be homogeneous in the classes that are grouped for any one objective, only the classes of the lowest category of the natural classification provide units that are homogeneous with respect to the variety of properties important for the large number of objectives for which technical groupings are made.

#### PRINCIPLES OF DIFFERENTIATION

##### *As they affect classes*

##### *1 A differentiating characteristic must be important for the objective*

The statements about each class are confined to (a) the differentiating characteristics, (b) their accessory characteristics, or (c) interpretations of both. A grouping based on a property that is not important for the objective leads to classes about which the statements possible are not the most numerous or the most important for the purpose of grouping. In spite of this fact, attempts to interpret a grouping made for one purpose in terms of another objective are common. The category of soil series, for example, is a grouping purely to show similarities in properties of the soil profile, but one sees repeated attempts to define suitability of an entire soil series for land use. The bases of grouping soils into series do not provide units homogeneous in all properties important for land use, the classes may range rather widely in such features as slope, degree of erosion, stoniness, and texture. A technical grouping of soil types and phases on the basis of an interpretation of all factors important in land use is required for this objective.

##### *2 A differentiating characteristic must be a property of the things classified or a direct interpretation for the objective*



If the grouping is a natural classification, the bases must be properties of the things classified. The objective is to see similarities and understand relationships among those properties; to classify on the basis of any other factor is to conceal those similarities and relationships. If soils were to be classified on the basis of factors of soil formation, for example, similarities and relationships among properties would be brought out only to the extent that the cause and effect relationships between factors of soil genesis and soil properties are known. The system formed would conceal relationships as yet unknown. A technical grouping of areas to show known relationships of soil genesis or to discover new ones, however, may well be based on those factors for correlation with properties of natural soil groups. In many technical groupings, various interpretations of characteristics may serve the objective best. A grouping of soils according to lime requirement might be based on an interpretation of the aggregate of known soil characteristics, including such measurable properties as pH and cation-exchange capacity of the various horizons. The grouping might be based on direct experimental evidence if that were available.

*3. The differentiating characteristic should carry as many accessory properties as possible for the objective.*

In the grouping in table 1, color was purposely chosen to differentiate in category 2 as a property that carries few accessory attributes. What can one say about dark-colored surface soils beyond the fact that they are dark, if he considers that such a group would include Chernozem, Solonetz, "Regur," Half-Bog, and varieties in which color was inherited from the parent material? Choice of a differentiating characteristic that carries many covarying properties, like reaction in category 2, increases the number of statements about each class and, therefore, the usefulness of the grouping.

*4. The class interval of a differentiating characteristic must provide classes homogeneous for the objective.*

When differentiation is based upon degree of expression of an attribute, the limiting value of that property between classes of a continuous series may be placed arbitrarily at any point in the series. Not all points within such a series are equally pertinent for a given objective, however, and the establishment of the class interval for the most useful grouping is not arbitrary. Accessory characteristics may not be straight-line functions of the differentiating property, and the best limits of classes for a given objective may be largely determined by them. The graph of percentage base saturation against pH, for example, is a characteristic titration curve. In northeastern United States, many mineral soils are roughly 30 per cent base-saturated at pH 5.0; 80 per cent, at pH 6.0; and 95 per cent, at pH 7.0. Thus a significant break in the curve occurs near pH 6.0; that pH is also associated with important changes in the solubility of iron, aluminum, and phosphorus. Soil classification must rely on the data of observation and experiment for establishment of the significant limiting values of classes. The points of greatest significance may vary not only among different objectives but also among different soils for the same objective.

#### *As they affect relationships among categories*

*1. The differentiating characteristic must classify all individuals in any single population.*

Nikiforoff<sup>3</sup> calls this the "principle of wholeness of taxonomic categories." Every category must include all existing individuals of the population; therefore, the differentiating

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<sup>3</sup> The author is indebted to C. C. Nikiforoff for many of the ideas expressed in this paper, particularly for the original expression of the principles of "wholeness of taxonomic categories" and "ceiling of independence of differentiating characteristics."



characteristic of each category must apply to all individuals, or some will remain unclassified. Violation of this principle was a serious error in Marbut's Classification of soils in 1935 (4); his "family groups," which were azonal and intrazonal soils, were not classified by the criteria used in higher categories. This does not mean that a system of classification must immediately provide a pigeonhole for every individual in every category. It must provide for expansion in the number of classes based on a given differentiating property to accommodate new individuals as they are discovered. (In many cases one class may be defined as the zero degree of the differentiating characteristic.)

*2. Greatly different "kingdoms" require different differentiating characteristics at the same level of abstraction.*

This principle rests upon a concept of degrees of difference among groups of things at different levels of abstraction. All living things might be considered a unit separate and distinct from all things that do not possess life. Each is a segment of the universe and might conceivably be included in one master natural scheme of classification. It would be futile, however, to attempt to differentiate within both groups on the basis of the same property; they have too few important things in common. All living matter, in turn, may be classified into two kingdoms, plants and animals, each of which is a distinct unit at a lower level of abstraction. Again it would be futile to attempt to differentiate within both on the basis of a single property. Such contrasting populations are differences in "kind," as Mill used the term (5), and require classification in different systems<sup>4</sup> using different criteria for differentiation at the same level of abstraction. Within the natural phenomenon called "soils," there may be populations that have so few important common properties that a single differentiating characteristic at a given level of abstraction would not frame the important classes in each. The breach between organic and inorganic soils may be of that order of magnitude.

*3. All classes of the same category of a single population should be based on the same characteristics.*

This is a corollary of the "principle of wholeness of taxonomic categories," but it needs some explanation in the light of the preceding concept. The objective of classification is accomplished by arranging the individuals in an orderly manner commensurate with order as conceived in the mind. To differentiate on different properties at the same categorical level complicates the problem of visualizing relationships. It should be resorted to only when two kinds of things have so little in common that the important properties of one do not occur in the other. At some level of abstraction, differences no longer outweigh common properties; at that and all lower levels the "principle of wholeness of taxonomic categories" applies.

*4. A differentiating characteristic in one category must not separate like things in a lower category.*

Every characteristic has a *ceiling of independence* above which it cannot be used to differentiate without separating like things in categories below it. This is illustrated in table 1, where the objective is to show the most important similarities related to color value and reaction. Color value, a property with few accessory characteristics, is used at the highest categorical level. When each of the two classes based on color is subdivided on the basis of

<sup>4</sup> The term "system of classification" is restricted in this article to those schemes in which a single differentiating characteristic is used throughout the population in any single category. Two or more such systems for distinctly different populations may be tied together by a common property in a more inclusive scheme.

reaction in category 1, four classes are formed. Two of those classes are acid and two are alkaline. In no category in the system are all acid soils segregated in one group and all alkaline soils in another. Reaction is associated with many accessory characteristics that make similarities in that property more significant than similarities in color value, but individuals of like reaction are separated by differentiation on the basis of color at a higher level. Differentiation at a high categorical level on any basis separates on that same basis throughout all lower categories; consequently, the properties used to differentiate at high levels of generalization must be more important for the objective than those used at lower levels. The importance of a differentiating characteristic must be commensurate with the level of abstraction at which it is used. Failure to observe this principle is a major error in Shaw's (7) classification of soils, in which origin of parent material as a differentiating characteristic in a high category separates like profiles throughout all lower categories.

#### CLASSIFICATION OF SOILS

##### *The soil as a population*

The dimensions of the ultimate individual of the soil population are fixed vertically by the thickness of the soil profile and horizontally by the practical limits of space required for its observation. Vertically, the soil unit must extend from the surface into the parent material; any lesser depth would divide the complete natural body. Horizontally, the limits are not sharply defined; the unit must extend in two directions far enough to allow sampling and accurate determination of the properties that can be observed in the field. It must be large enough to permit observation of relationships of horizons to the rooting of plants. An almost infinite number of these individuals make up the population—the soils of the world.

It is impractical, however, to attempt to deal with all these small units in any system of classification or in most practical problems involving use of the land. The range of the properties of each is too narrow to be significant; their numbers are too great to allow individual treatment; the area represented is too small to serve as a practical land unit in most operations. These individuals, however, are the sampling units upon which must depend definition of soil of larger areas feasible of treatment for most problems. These more inclusive units, as typified by the soil type or phase, may be considered classes of the lowest category of soil classification. They are more than a categorical grouping of individuals, however, because their variation is fixed partly by the geographic association of the ultimate individuals in areas large enough to be feasible of treatment. The definition of these classes is a problem in sampling to determine the characteristics of the modal profile and the deviations from it. Just as in the definition of a species of plants, no attempt is made to study all individuals and group them into a class of the lowest category. A sample is drawn, and from it are estimated the properties of the class.

##### *Sources of criteria*

For the most part, the criteria used to classify are those that can be observed or determined rapidly by simple tests in the field. This is inevitable because the practical limitations imposed by requirements of an adequate sample (1) of such a variable population preclude laboratory determinations as criteria for applica-

tion on an areal basis. Consequently, until techniques are developed that will allow rapid chemical determinations in the field, one should expect homogeneity of chemical properties of soil units only to the extent that they are accessory to the observable characteristics used to classify in the field.

One is not confined to direct observation, however, in choosing criteria or their class intervals. Controlled experiments establish relationships that enable selection of those criteria to which many properties that cannot be observed are accessory. They not only indicate important criteria but also indicate significant class intervals.

For every controlled experiment there are thousands of natural experiments from which criteria of properties that cannot be observed readily may be deduced. Data from these experiments are not in orderly arrangement; they must be collected in many places, classified, and applied to soils by the correlation methods of science. The correlation of natural vegetation types with soil conditions, for example, is a principle criterion for the placement of soil boundaries. The behavior of crops under known management may indicate soil properties that cannot be observed easily.

Enough is known about soil formation to establish broad factors of the process and some of their effects. We expect a difference between two soils if any one of the factors varies. A change in one of the factors is a warning to look at the soil again if no differences have been observed. Genetic factors, though not criteria of classification in themselves, are indexes to soil properties that are criteria.

### *Criteria of classification*

Soil classification is passing through a series of approximations in which the system is being built from the lowest category upward by a process of reducing homogeneity in each successively higher category. If our knowledge were complete, we should be able to choose the differentiating characteristic of each category, but at present not only must we establish the importance of many known relationships but undoubtedly we are still unaware of many relationships that will be discovered. Our choice of differentiating characteristics in the higher categories is limited by our knowledge not only of soil properties but also of relationships among soil properties. As a direct result of requirements imposed by the "principle of a ceiling of independence of differentiating characteristics," the limitations imposed by lack of knowledge are greater, the higher the level of generalization in the system. Let us examine the possible criteria at our disposal.

No one has yet improved appreciably upon the following list of criteria proposed by Marbut (3), for differentiation among soils at the level of the soil type:

1. Number of horizons in the soil profile.
2. Color of the various horizons, with special emphasis on the surface one or two.
3. Texture of the horizons.
4. Structure of the horizons.
5. Relative arrangement of the horizons.
6. Chemical composition of the horizons.

7. Thickness of the horizons.
8. Thickness of the true soil.
9. Character of the soil material.
10. Geology of the soil material.

Each of the 10 factors listed varies narrowly in a soil type within the limitations of precision of their measurement. Long experience with the soil type has proved that it, as defined, is a unit adequately homogeneous for most of the practical problems of the land so far as the soil profile is concerned. No better unit has been suggested at that categorical level. Cases of inadequate homogeneity are the result either of lack of precise application of one or more of the criteria listed or of the importance of features other than characteristics of the profile, such as slope or degree of erosion. Lack of precision is not a fault of the system but of its application; techniques for feasible evaluation of chemical properties, for example, are not adequate. Such characteristics as slope are differentiated in the soil phase or its equivalent in practical problems. One must conclude, therefore, that Marbut's criteria provide a workable basis for classification of soil profiles in the lowest category; when properly applied, they provide units about which the number, precision, and importance of statements are adequate for practical problems in soils.

Now consider the implications of the "principle of accumulating differentia" in relation to the proposition that the properties listed by Marbut are adequate for differentiation at the level of the soil type. All of those properties except the one used to differentiate soil types within a soil series must be accumulated from the differentiating and accessory characteristics of higher categories. The list undoubtedly is not a complete accumulation of all those characteristics, but each property in the list must be either differentiating at a higher level or accessory to a property that is differentiating. It would be sheer accident if any property could be found to differentiate at higher categorical levels that is not either (a) a characteristic listed by Marbut, or (b) a characteristic to which one of the properties listed by Marbut is accessory.

The properties listed by Marbut were not intended as bases of differentiation in higher categories, and careful consideration will show that no single characteristic listed could be used at a level higher than one category above the soil series without exceeding its ceiling of independence. Its use would separate like things in lower categories and defeat the objective of a natural classification. One must conclude, therefore, that these properties are accessory characteristics of those attributes whose ceilings of independence are high enough to justify their use in the higher categories. This is one important reason why the "formula" type of system in which individual soil properties are accumulated in a symbol in some specified order is not a natural classification.

The first step in the selection of differentiating characteristics of higher categories, therefore, is to define the characteristics to which the properties listed by Marbut are accessory. Most of those listed are characteristics of individual horizons. All of them, collectively, plus inferences from them, however, define the whole soil, not only in terms of all of its horizons but also in terms of rela-

tionships among horizons. It is to this definition of the soil type that one must turn for criteria whose ceilings of independence permit their use at high categorical levels. A Podzol, for example, is not just any soil with a bleached horizon; it is a complete natural body definable in terms of all of its horizons *and the relationships among them*.

At a given level of abstraction, for example, the kind and sequence of horizons defines a specific "kind of profile." This is a characteristic of the whole soil and has a ceiling of independence far above that of soil texture. The degree of expression of those horizons is also a property of the whole soil; its ceiling of independence is obviously below that of "kind of profile" but still above that of soil texture. Kind of parent material is reflected throughout the whole soil; its ceiling of independence is below that of degree of expression of horizons but slightly above that of soil texture—in fact, it is roughly commensurate with the level of abstraction of the soil series as used at present. It is from properties such as these that the criteria for differentiation in the various categories above the soil type must come. Their definition is controlled by the state of knowledge about specific soil characteristics and especially about relationships among horizons. We may expect many approximations before knowledge will be adequate to frame, in final form, the generalizations necessary for definition of appropriate criteria at the various categorical levels.

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## SOIL CLASSIFICATION AND THE GENETIC FACTORS OF SOIL FORMATION

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The soil scientist, by classification and correlation, derives general principles about soil genesis and the effect of each genetic factor. Though he cannot arrange the factors in desired proportions and combinations for an experiment, he can select and observe natural situations which constitute "experiments" suited to his purpose. After observing, describing, and classifying the soils and genetic factors in one area, he can study them in another area. He then can compare soils and sets of genetic factors alike in all, alike in many, or alike in few characteristics. For example, if two sets of factors are identical except for parent materials, correlation of soil properties will make it possible to infer and estimate the effects of the various properties of the parent material. Similarly, differences between two soils will reveal the existence of significant dissimilarities in the genetic factors affecting them. Of course, two natural situations usually show differences in more than one factor and the influence of each is diminished or enhanced by interaction with the others. Measurement of the influence of each is, therefore, more difficult and less precise than in fully controlled experimental conditions. Nevertheless, the method of correlation tests and evaluates the factors involved in essentially the same way as do man-made experiments.

Once the effects of a soil-forming factor are known, any recognizable change in the factor will indicate a probable change in soil. For example, with other factors constant, each kind of parent material is likely to give rise to a soil of distinctive characteristics. Where glacial outwash, underlain by stratified gravel, gives way to unstratified clayey till, the soil will likewise change, perhaps from a well-drained, brown, and productive one to a poorly drained, mottled, and unproductive one. Usually the till and the outwash differ in both elevation and surface configuration. Thus, two soil-forming factors, parent material and relief, each consisting of many components or subfactors, may change at once along an easily recognized line, which will also be a soil type boundary. This boundary, however, can be established only when inspection of the soil verifies the occurrence of change in soil and eliminates the possibility of mere irregularities on the surface of the outwash. In areas of exceptionally uniform parent material and topography, changes in soil may result from underground seepage or variations in soil structure not apparent on the surface. When this happens, the soil

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scientist must depend entirely upon profile examinations to locate the boundaries between soil units. Usually, however, the trained observer will discern significant differences in vegetation, relief, or surface appearance which coincide or are likely to coincide with the boundaries of soil types.

#### SOIL CLASSIFICATION AND THE TIME FACTOR

Where a river has built a succession of terraces in a valley, the higher terraces will represent earlier depositions than the lower. Each successively lower one may consist of essentially the same materials and have the same vegetation and slope as the one above, yet the soils formed on each will differ in age and usually in profile. In such a case, the soil type boundaries at the edge or rim of each terrace will divide types differing in age. In some areas, however, subsequent deposits of till or loess have blanketed a series of terraces with materials of the same age.

In California, some portions of alluvial fans are being constantly built up by fresh deposits, whereas other portions have received no deposition for centuries. The soils present on these fans (30) are sandy and gray or grayish brown on the most recent deposits; they are sandy and have slight B horizon development on relatively young deposits; they have sandy loam A and sandy clay loam B horizons on old deposits; and sandy loam A and clayey or cemented B horizons on the oldest deposits. The Mississippi River delta deposits ranging in age from recent to Pleistocene have given rise to soils differing considerably in profile (31).

Some of the best-known examples of soils of differing age are found in north-central United States where four or five glacial advances and interglacial loess depositions have occurred. The soils developed differ markedly in character. The younger soils generally are more permeable and are better aggregated than the older ones, which are strongly leached and have dense, slowly permeable B horizons. For example, the Nappanee soil of Indiana on shaly glacial till of Wisconsin age has a gray silt loam A horizon and a mottled silty clay B horizon, 10 or 15 inches thick, over slightly weathered calcareous till. The Vigo on similar till of greater (Illinoian) age and with comparable drainage also has a gray silt loam A horizon but a mottled, compact silty clay loam B horizon, 2 or 3 feet thick, over plastic, sticky silty clay loam weathered from the till and leached of lime to a depth of 8 to 12 feet (4).

Moraines left by retreating glaciers of the present day also are the sites of related soils differing in age. Chandler (8) found that the soils on moraines deposited by the Mendenhall glacier in Alaska showed no differentiation into horizons in 15 years but had an accumulation of 5 inches of litter ( $A_0$ ) and a brownish A horizon in 250 years. On moraines approximately 1,000 years old, a true Podzol with an ashy gray  $A_2$  horizon, 2 to 4 inches thick, and a dark brown B horizon, 6 to 8 inches thick, had formed.

Smith (28), by estimating rates of deposition and leaching of loess, was able to assign relative ages to Peorian loess of different thicknesses in Illinois. He compared two soils developed from loess on slopes of 3 to 7 per cent, on which little or

no erosion had occurred. Both soils were formed under prairie grass and in a subhumid to humid climate within a relatively short distance of each other. Some of the differences between them, chiefly ascribable to age, were summarized in table 1.

Volcanoes have deposited lava and ash at various times, and all stages of soil development may be found on these deposits. In tropical areas, soils form rapidly, and fertile soil containing 2 per cent organic matter may form from volcanic ejecta in 14 years (12). Nearby lateritic and relatively infertile soils on older deposits may have a pH of 5.0 or less even though developed from alkaline materials similar to those of recent deposits. On the other hand, very dense, resistant, or infertile materials may change very slowly in any climate, both because they are little affected by weathering and because they do not support abundant vegetation.

TABLE 1  
*Comparison of two Illinois soils differing chiefly in age (28)*

RELATIVE AGE	A HORIZONS				B HORIZONS	
	Color and texture	Properties at 8-inch depth			Color, texture, and consistence	Maximum content of colloid (<1 $\mu$ diameter)
		Content of colloid (<1 $\mu$ diameter)	Content of organic carbon	Base saturation		
		<i>per cent</i>	<i>per cent</i>	<i>per cent</i>		<i>per cent</i>
1.0	Very dark brown silt loam	23	1.8	75	Dark yellowish brown silt loam, friable	29
1.7	Dark grayish brown silt loam	20	0.7	35	Light brownish gray silty clay, compact and plastic	44

#### SOIL CLASSIFICATION AND THE PARENT-MATERIAL FACTOR

Soil parent material consists of geological deposits and formations, mineral or organic, consolidated or unconsolidated, on which soil-forming processes begin to act (15, p. 54). When soil-forming processes have acted for a long time, the properties of the resulting soil generally differ greatly from those of the parent materials. Some of the influences of the parent materials, however, are long apparent or never completely erased. The Maury soils in the bluegrass region of Kentucky and the central basin of Tennessee are derived from limestone strata high in phosphorus. These soils have remained rich in phosphorus, although leaching has removed the lime and made them acid (32, p. 1068). More properties of the parent rock persist in arid regions than in humid regions. On steep slopes where geologic erosion tends to keep pace with soil formation, the properties of the parent materials largely determine those of the soils.

A rigorous definition of a soil parent material requires at least a statement of the mineralogical and chemical composition, the size distribution (texture) of the

component particles or crystals, and the arrangement of these component particles relative to one another (for example, schistosity or porosity). Each of these properties of the soil parent material may be an independent variable with a powerful influence upon soil formation. For example, soils formed from granite in humid temperate climates are frequently coarse textured and acid; in cooler climates they often have superficial humus layers of the mor types (16). Soils derived from diorite and the most basic gabbros under similar conditions usually are deeper and better supplied with calcium and phosphorus and have mull types of humus layers. These soil differences are associated with differences in the mineralogical or chemical composition of parent materials, since these soils are all derived from coarse-textured, solid rocks having random orientations of the individual crystals. Plagioclase feldspars and basic rocks have been reported to weather directly to gibbsite in the tropics, whereas the alkali feldspars of acidic rocks weather to kaolinite (13: 23, p. 96).

Coarse-textured granites weather more rapidly in humid, temperate climates than the finer-grained granites, porphyries, and rhyolites, although all have similar mineralogical and/or chemical compositions. On hills or steep slopes coarse-grained granites commonly give rise to deep Lithosols (25) while shallow Lithosols form from rhyolites and porphyries (14, p. 53: 21, p. 91).

Structural differences of the soil parent materials also influence the properties of soils. It has been reported that gneiss standing on edge weathers more rapidly than granite of similar texture and mineralogical composition (14, p. 51). Mohr (23, p. 89) observed that obsidian may weather to a depth of only a few millimeters, even under tropical conditions, while a fine volcanic ash deposit of similar chemical composition is weathered completely.

These properties of parent materials may or may not be related. For example, the clay contents of the B horizons of soils derived from Wisconsin till in north-eastern Illinois have been shown to be directly related to the clay content of the till (29). Field observations have also indicated that the finer the texture, the lower the permeability of the till. This is borne out by data showing that the depth to which carbonates have been removed by leaching decreases as the clay content of the till increases (table 2). In other areas, however, these differences in mineralogy and permeability (structure) of the till may be independent of the texture of the till. For example, on the late Wisconsin drift in Ohio, the lime content, mineralogical composition, and texture of the glacial till are each capable of producing a distinctly different soil (9).

Very complex relationships between parent materials and soils may be found in areas derived from folded thin bedded sedimentary rocks (for example, Armuchee and Sequoia series in the Southern Appalachian Valley) or where thin glacial, alluvial, or loessial deposits lie on different substrata. In these cases it is not always clear from field observations what portion of the soil profile developed from each kind of parent material; however, laboratory methods (18) can throw considerable light upon soil genesis and the relationships of parent materials to soils.

## SOIL CLASSIFICATION AND THE RELIEF FACTOR

Some of the relations between relief and soils are obvious to the casual observer. For example, the common terms "lowland soils" and "upland soils" imply a correlation between relief and soil. Several other soil-relief relations, mainly those occurring within a single landscape, are well known and have been described by various writers (4, 11, 17, 20, 24). Principal among these are the correlations between relief and (a) soil differences related to drainage, especially coloration and degree of mottling, (b) thickness and/or organic matter content of the A horizons, (c) depth of solum, (d) degree of horizon differentiation, (e) salinity, (f) kind of hardpan, and (g) nature of the parent materials.

One of the best-known examples of a soil-relief sequence in the United States is the Miami catena described by Brown and Thorp (3). This soil-relief se-

TABLE 2

*Relation between the properties of Wisconsin glacial till in northeastern Illinois and the soils derived from it*

SOIL SERIES	DEPTH TO CARBONATES (33)	CLAY CONTENT OF B HORIZON (29) <2 $\mu$ *	PROPERTIES OF ASSOCIATED TILL (33)		
			Permeability	Clay content <2*	CaCO <sub>3</sub> equivalent
	<i>inches</i>	<i>per cent</i>		<i>per cent</i>	<i>per cent</i>
Clarence.....	25.9 $\pm$ 0.52†	>53	Impermeable	>44	20.6
Swygert.....	28.8 $\pm$ 0.54	53-46	Slowly permeable	44-35	24.1
Elliott.....	32.0 $\pm$ 0.48	46-38	Slowly to moderately permeable	35-25	28.2
Saybrook.....	36.1 $\pm$ 0.62	<38	Permeable	<25	27.8

\* Interpolated from 5 $\mu$  and 1 $\mu$  determinations. Values listed were determined from the graphical relationship between the maximum clay contents of the B horizons and the clay content of the parent materials, as determined by Stauffer (29) and the clay contents of the till, determined by Wascher and Winters (33).

† Standard error of the mean.

quence, or "toposequence" according to the terminology suggested by Jenny, (15) consists of soils developed from calcareous loamy till of Wisconsin age in the oak-hickory forest area of the east-central United States (table 3). The climate is temperate-humid; the zonal soils are Gray-Brown Podzolic. Similar drainage or relief sequences occur on various other parent materials throughout the warm-temperate forested, or Podzolic, region.

In the subhumid and semiarid regions, where high water table is rare, the correlation between soil color and topography changes; it reflects the less arid local climate in the areas of concave surface, and the more arid climate in areas of convex and steep surface. Here the usual toposequence or catena consists of Lithosols on the steeper slopes, and successively darker and deeper soils with increasingly more clayey subsoils as the slope decreases or as the surface changes from convex to concave. In a sense, this is a microclimatic sequence, which consists of soils ranging from those that lose runoff to those that receive runoff.

In the subhumid and arid regions the soil characteristic most commonly associated with high water table is salinity. Laterite hardpans, much of the caliche

TABLE 3  
*Relief, drainage, and soils of the Miami catena*

RELIEF	NATURAL DRAINAGE	SOIL
Steep upland	Very rapid external	Hennepin series: A <sub>1</sub> horizon 3 to 6 inches thick, dark grayish brown, granular, high in organic matter, neutral to alkaline; A <sub>2</sub> horizon yellowish gray, friable, neutral to mildly alkaline; B horizons absent; solum 10 to 20 inches deep over calcareous till. Regosols (Azonal).
Level to steep upland	Medium to rapid	Miami series*: A <sub>1</sub> horizon 2 to 4 inches thick, fine granular fine sandy loam, loam, or silt loam, neutral to mildly alkaline; A <sub>2</sub> horizon pale brown to grayish yellow, thin platy fine sandy loam, loam, or silt loam, acid, about 9 inches thick; B <sub>2</sub> horizon yellowish brown, loam to clay loam (one textural grade heavier than the A horizons), coarse granular or nuciform, friable, unmottled, slightly to medium acid, about 18 inches thick; solum about 3 feet deep over till. Gray-Brown Podzolic soils.
Very gently sloping upland; mostly plane	Medium to slow external; slow internal; moist-dry	Crosby series*: A <sub>1</sub> horizon about 2 inches thick, grayish brown to gray, weakly aggregated, medium acid; A <sub>2</sub> horizon light brownish gray to very pale brown, thin platy, strongly acid; B <sub>2</sub> horizon heavy clay loam, strongly mottled gray and brown, firm, strongly acid; depth of solum over calcareous till 3 to 3½ feet. Planosols.
Level flats and shallow depressions having a natural drainage outlet	Very slow external and internal	Bethel series: A <sub>1</sub> horizon about 3 inches thick, gray, platy, strongly acid; A <sub>2</sub> horizon light gray to almost white, platy or massive, strongly acid; B <sub>2</sub> horizon about 6 inches thick, gray mottled with yellowish brown and brown, silty clay, very firm, blocky, nearly impervious (a claypan); solum about 3 feet deep over calcareous slightly weathered glacial till. Planosols.
Shallow enclosed depressions	Very slow to no external; very slow internal; water table near surface; moist-wet	Brookston series: A <sub>1</sub> horizon 6 to 16 inches thick, very dark gray to very dark grayish brown, very strong granular, contains some 8 per cent organic matter in upper 6 inches, about neutral; subsoil 2 or 3 feet thick, mottled gray and yellowish brown, heavy clay loam with some 10 per cent more colloid than surface soil, firm, noncalcareous; solum 3 to 4 feet deep over friable calcareous or alkaline till. Shallow Wiesenboden soils.
Medium-depth enclosed depressions	No external; water table at surface; always wet	Clyde series or a close relative: A <sub>1</sub> horizon 10 to 20 inches thick, black, very strongly granular, about neutral, contains some 10 to 15 per cent organic matter in upper 6 inches; subsoil gray more or less mottled with browns (a glei layer), of heavier texture than surface soil, neutral or alkaline. Wiesenboden.
Deeper depressions	Permanently saturated; water table above surface	Carlisle muck†: Alkaline to slightly acid, granular, very dark brown muck several feet thick over inorganic substrata.

\* In current correlations in some areas, it has been necessary to recognize a moderately well drained Gray-Brown Podzolic soil, Celina, lying between the Miami and the Crosby.

† Although Carlisle muck falls in the soil association with the other members of the Miami catena, it does not fall taxonomically within the catena since the parent material is peat rather than glacial till.

of the southwestern United States, the Solonetz soils, most or some of the ferruginous hardpans in soils of dry regions, and probably the duricrusts occurring along water courses in Australian and other deserts are all correlated with water tables, present or past, and these, in turn, are related to relief.

Relief, itself, is frequently determined by kind and age of the surface formations, climate, vegetation, and other factors, and its effect on soil varies profoundly in relation to the other four factors of soil development. For this reason, it is not always an independent factor in soil development, strictly speaking; its relations to soil are seldom those of direct cause and effect.

In many instances the parent materials do not remain constant in various parts of a landscape. The crests of hills may have thin, shallow soils developed in residuum from resistant formations; the valley slopes, deeper soils developed in softer rocks or in unconsolidated material eroded from the hills; and the valley floor, young soils developed in alluvium. These are, however, many and extremely important exceptions to this generalization. One of these is that occurring on plateaus cut from old peneplains. There the summit of the plateau has old, deep soils, and the parent rock may be of any character; shallower, less well developed soils occupy the valley slopes, and the valley floor of soils developed in alluvium may or may not be present. Another extensive deviate occurs in alluvium-filled desert valleys in which alluvial fans and aprons of various ages occur. Here the age of the deposit and present soil may be so dominant in determining the soil character that the direct effects of relief and drainage become masked and undetectable.

Some of the most complex soil-relief relations occur in the tropics on truncated old surfaces underlain by laterite hardpan. An outstanding example of this occurs in western Australia, where an old peneplain underlain in sequence downward by laterite, kaolinized clay, partly weathered bedrock, and unaltered bedrock has been rejuvenated and subsequently dissected. In this case, the knolls and elevations have soils developed in laterite. Occasional higher knolls have a remnant of the old podzolic soil developed over the laterite. Immediately down-slope from these soils developed in laterite, there is a broad band of soils developed in the kaolinized clay, more or less contaminated with scree and talus from the laterite. In succession at lower elevations are areas of (a) soils developed in residuum from the less altered bedrock, and (b) soils developed in alluvium.<sup>2</sup> Here the present soils are superimposed on relict horizons from a previous soil association.

#### SOIL CLASSIFICATION AND THE LIVING-ORGANISM FACTOR

One of the outstanding examples of the influence of vegetation on soil profile characteristics, and hence soil classification, is the contrast between prairie soils and forest soils developed from the same kind of parent material. Jenny (15) quotes an example from data of Bray. In the Illinois area studied by Bray, there appear to be no differences in the deep loess parent materials, yet certain areas support forest vegetation and others prairie grasses. The climate is characterized by a rainfall of 30 to 35 inches and a mean annual temperature of 53°F. Although the profiles studied were from nearly level cultivated fields, distinct differences due to influence of the native vegetation were found. The forest soil

<sup>2</sup> From oral descriptions by C. G. Stephens, Waite Institute, Adelaide, South Australia. Published descriptions appear in the *Bulletins of the Australian Council for Scientific and Industrial Research*.

(Rushville silt loam) compared with the prairie soil (Grundy silt loam), contained less organic matter, had lower pH values and smaller amounts of exchangeable bases from the surface to a depth of about 3 feet, and had a greater accumulation of colloids in the B horizon. The forest was responsible for producing a Planosol in this instance, while the grass produced a Prairie soil. These results are rather similar to those reported by Rost (26, 27) and McMiller (17) for certain Minnesota soils.

Forest tree foliage varies greatly in its influence upon soil acidity, depending upon its content of basic ions, principally calcium. This factor of composition of the leaves is largely associated with the species of tree rather than with soil characteristics. Chandler (6) has shown that red cedar trees may increase the

TABLE 4

*Properties of soil profiles developed beneath three forest types in the Adirondacks, New York*

FOREST TYPE	HUMUS LAYER TYPE AND GREAT SOIL GROUP	HORIZONS	ORGANIC MATTER CONTENT	pH	EXCHANGE CAPACITY	BASE SATURA- TION
			<i>per cent</i>		<i>m.e./100 gm.</i>	<i>per cent</i>
Spruce	Greasy mor	A <sub>0</sub> (H-layer)	88.6	3.45	148	13
		A <sub>2</sub>	3.9	4.60	8	20
		B <sub>1</sub>	20.6	4.75	56	27
		B <sub>2</sub>	12.0	4.95	29	27
		C <sub>1</sub>	0.9	5.05	3	23
Spruce-Hard- wood	Granular mor; Podzol	A <sub>0</sub> (H-layer)	73.6	3.74	129	20
		A <sub>2</sub>	2.2	4.03	5	15
		B <sub>1</sub>	13.8	4.35	49	21
		B <sub>2</sub>	14.0	4.86	32	29
		C <sub>1</sub>	2.0	5.27	3	30
Hardwood	Fine mull; Brown Podzolic	A <sub>0</sub> (F-layer)	79.7	5.56	122	72
		A <sub>1</sub>	33.3	5.05	56	47
		B <sub>1</sub>	17.0	5.14	31	36
		B <sub>2</sub>	12.5	5.24	27	34
		C <sub>1</sub>	2.8	5.32	5	34

pH of the A horizon from 5.3 to 6.9 within 30 years. Foliage of this species usually contains more than 3 per cent calcium.

Chandler (7) has studied the influence of different forest types upon soil formation in the Adirondack section of New York State. Cady (5) showed that the parent materials of all the soil types studied had the same mineralogical composition. All were developed from compact glacial till, and no environmental differences other than vegetation could be identified. Consequently, on these soils vegetation can be considered an independent variable. The three forest types studied were briefly described as follows: 1. Red spruce type composed chiefly of red spruce, with admixtures of yellow birch, balsam fir, red maple, American beech, and eastern hemlock. 2. Red-spruce-sugar-maple-beech type, principally composed of these species with admixtures of yellow birch, red



maple, balsam fir, and hemlock. 3. Sugar-maple-beech-yellow-birch type, principally composed of these species with varying components of basswood, white ash, black cherry, and hophornbeam. For convenience these types are referred to as spruce, spruce-hardwood, and hardwood types, respectively.

The spruce and spruce-hardwood types so influenced the soil-forming processes as to give rise to a Podzol soil, classified as Becket sandy loam. The hardwood type produced a Brown Podzolic soil, Essex sandy loam. As with forest and prairie in Illinois and Minnesota, vegetational differences caused the formation of soils belonging, not only to different soil types, but to different great soil groups. Some of the more important differences in the resulting profiles are summarized in table 4. More detailed profile descriptions are given by Donahue (10).

To study the possible causes of these differences, samples for chemical analysis were taken from the foliage of trees surrounding pits dug for profile sampling. The analytical data indicated that the calcium content of the foliage was correlated with the profile characteristics. To give this factor quantitative expression, the proportion of the basal area of each tree species around the soil pit was multiplied by the calcium content of the leaves for each species. Summation of these results by forest types gave the following relative calcium contents for the three different conditions:

FOREST TYPE	RELATIVE CALCIUM CONTENT
Spruce.....	100.0
Spruce-hardwood....	106.6
Hardwood.....	180.6

The small difference between the spruce and spruce-hardwood types correlates well with the similarity of the profiles beneath these types.

It should be emphasized that vegetation is one component of the over-all soil-forming factor, organisms. Other important components are bacteria, fungi, earthworms, rodents, and man. Man is continually making vegetation an independent variable by planting different crops upon the same soil type in the same region. The influence of these crops on the soil has often been studied; for example, the influence of alfalfa as contrasted with bluegrass upon soil nitrogen content.

Vegetation can be used as an aid in the delineation of field boundaries in soil survey work in certain regions, especially in reconnaissance surveys in some non-agricultural regions. Lightly cutover forested areas in the Adirondack Mountains of New York State, the northeastern part of Maine, the White Mountains of New Hampshire, and many areas in eastern Canada are examples of this relationship. Nearly pure spruce stands on steep mountain slopes often indicate Lithosols. The mixed forest types usually denote Podzols. Pure hardwood forests are usually growing on Brown Podzolic soils. Low-lying pure coniferous types are associated with sandy outwash or may represent soils of poor drainage ranging from Ground-Water Podzols to Half-Bog and Bog soils. To use this

distribution of vegetation effectively in locating soil boundaries, the surveyor must have intimate knowledge of the soil-vegetation relationships of the region. He may even determine the distribution of forest types from aerial photographs and deduce therefrom the distribution of the soils.

Striking relationships between the distribution of vegetation and differences in soil parent materials often exist. One observed by Chandler occurs where the black Hills of South Dakota protrude into the eastern edge of Wyoming. At the edge of these hills, tongues of Ponderosa pine forests reach out into typical arid grassland vegetation. No evident temperature or other climatic differences exist which might account for development of forest vegetation in one case and desert grasses in the other. Chandler examined the soil under both the grass and the forest vegetation over a distance of 50 miles. In all cases, he found that the pine forests were growing on soil developed from a black shale, whereas the grasses occurred on gravelly soils developed from old water-worked deposits in which shale was virtually absent. Laboratory examination revealed that the forest soil was strongly acid (pH of about 4) whereas the grassland soil was alkaline (pH of about 8.4). Apparently the black shale contained considerable sulfur, which was not leached out under the mean annual rainfall of about 15 inches. In this area, aerial photographs would have adequately shown the soil boundaries, thus eliminating considerable field work. As in many other instances, vegetation was acting as a dependent variable.

#### SOIL CLASSIFICATION AND THE CLIMATIC FACTOR

The climatic factor expresses itself through the moisture and energy it contributes to an environment. It influences soil genesis directly, but its indirect action, through the organisms for which it supplies energy and a suitable environment, is often of equal or greater significance. Sun energy which is stored in plant substances by photosynthesis is released during digestion and decomposition by multitudes of organisms. When released, it assumes the form of chemical and physical energy which engenders or modifies many fundamental soil reactions and soil processes.

Within limits, the organic matter content of soils increases as precipitation increases and as temperatures fall. Clay content tends to increase as precipitation increases and as temperature rises. The degree of aggregation of soils tends to increase from arid to subhumid regions but decreases from subhumid to superhumid if temperatures are low to moderate. The degree of aggregation increases with temperature when moisture is abundant. Many other broad relationships between soil characteristics important in soil classification and climatic differences have been recognized (1, 15).

Blumenstock and Thornthwaite (2) have concisely summarized the distribution of the broad classes of climate, vegetation, and soils on a hypothetical level continent (table 5). Soils on extensive land areas, such as continents, are affected by the general or macroclimate considered in table 5 but the soil scientist is often concerned with soil series and types produced by the local or microclimate. Examples have already been given of the manner in which the runoff from slopes

affects the microclimate. A slope exposed to sun and wind from the south and west will be drier and warmer than one facing north and east. A valley at right angles to the prevailing wind or a small area inside a dense forest will be cooler, less affected by winds, and more humid than near-by level grassy uplands.

TABLE 5

*Schematic representation of distribution of climatic types, vegetative formations, and major zonal soil groups on a hypothetical level continent*

Condensed from Blumenstock and Thornthwaite (2)

	Dry cold			Wet cold		
Climatic Types and Vegetative Formations	Perpetual Snow and Ice					
	Tundra					
	Taiga					
Climatic Type	Arid	Semiarid	Subhumid	Humid	Wet	
Vegetative	Desert grasses and shrubs	Steppe	Grassland	Forests	Rain forest	

Dry hot

Wet hot

A. Distribution of climatic types and vegetative formations

Dry cold

Wet cold

Perpetual Snow and Ice			
Tundra Soils			
Podzols			
Sierozems and Desert soils	Chestnut and Brown soils	Prairie soils and Chernozems	Podzols
			Gray-Brown Podzolic soils
			Red and Yellow Podzolic soils
			Lateritic soils

Dry hot

Wet hot

B. Distribution of major zonal soil groups on a climatic base

Each of these microclimates has a soil environment differing from the general climate, an environment that will produce soils differing in major or minor characteristics from those of the region as a whole.

Perhaps the most striking examples of the influence of climate on soil genesis and classification are found on mountains, particularly on those whose bases are in hot, arid regions but whose summits reach into the cool, moist air of high alti-

tudes. Belts of successively cooler and more moist conditions and parallel belts of vegetation and soils occur from base to summit on such peaks. This vertical zonation presents within a few miles a range of soils comparable to that usually found over horizontal distances of hundreds or thousands of miles. Martin and Fletcher (19), after summarizing studies of vertical zonation by various investigators, present data showing that the soils of Mt. Graham, Arizona, and vicinity constitute a succession having representatives of several of the zonal soils. Data for three of the zones on Mt. Graham are condensed in table 6. The data for mean annual temperature and rainfall were compiled from records from Mt. Graham and other locations in Arizona. The soils at elevations above 4,100 feet were derived from residual materials on gneissic bedrock; those at lower elevations were derived from transported material in which gneissic materials were abundant. The soils in the various zones on Mt. Graham are comparable

TABLE 6

*Climatic zones and associated vegetation and soils on Mt. Graham, Arizona, and vicinity (19)*

ELEVATION ABOVE SEA LEVEL	MEAN ANNUAL TEMPERA- TURE	MEAN ANNUAL PRE- CIPITA- TION	TYPICAL VEGETATION	PROPERTIES OF SURFACE SOIL				GREAT SOIL GROUP
				Color	Depth	pH	Organ- ic carbon	
<i>feet</i>	<i>°F.</i>	<i>inches</i>			<i>inches</i>		<i>per cent</i>	
9,860	44.2	24.4	Fir, spruce, aspen	Dark yellow- ish brown	0-4	5.69	.87	Gray-Brown Podzolic
3,800	61.6	13.8	Desert grasses	Weak orange to moderate yellowish brown	0-4	6.55	.26	Reddish- Brown
3,360	64.5	10.1	Mesquite, creosote bush	Moderate yellowish brown	0-3	6.72	.14	Red Desert

to, although not identical with, zonal soils occurring in extensive areas elsewhere in North America. This remarkable similarity in the soils of mountain and continental zones is cogent evidence of the powerful influence of the climatic factor.

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## LOWER CATEGORIES OF SOIL CLASSIFICATION: FAMILY, SERIES, TYPE, AND PHASE

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The theories, techniques, and procedures the scientist chooses to employ in establishing lower category units are influenced by his objectives. In the lower categories, especially type and phase, the main concern is with the creation of soil units that have homogeneity in properties, relevant to the making of predictions in the use and management of the soil to grow plants. Engineering, hydrologic, and other properties must be considered in some instances. Selection of differentiating properties and decisions on permissible range in properties are important problems in establishing soil units.

### THE SOIL UNIT OR INDIVIDUAL

It is generally recognized that the unit of observation and study is the soil profile, or the vertical section of a cut or trench. The term "solum," coined by Frosterus and introduced into this country by Marbut, has come to be commonly accepted as that part of the profile in which parent material has been altered during the formation of the soil. The soil profile, on the other hand, has come to mean, in common usage, the solum plus the parent material. These concepts find their greatest usefulness in areas where the parent material has vertical uniformity or is, as suggested by Jenny (3), isotropic in character. Where the parent material is of sufficient vertical thickness, it plus the solum may include all of the profile significant to agriculture. Such a situation is depicted in figure 1, where the soil is formed in deep loess.

There are many situations, though, where the parent material does not have vertical uniformity. One such situation is illustrated in figure 2. Here, the parent material consists of silty material overlying a gravel stratum, and the so-called solum, including A and B horizons, is formed in the silty material. The gravel stratum, although not a part of the solum, is a part of the vertical cross-section which is important to the growing of plants. In other instances, the parent material may be a silty material overlying slowly permeable till or shale material.

The range in properties of the soil unit or individual to be created or defined will depend on two factors, namely, the pedogenic concepts, and the practical uses of the soils. The relative importance of the two viewpoints cannot be quantitatively determined. It can be argued that a difference in management requirements will be reflected to some extent in the solum. Although it is difficult in some cases to obtain pedologic criteria, the practical need for a separation may be very evident. This is illustrated in table 1. The Galva and Sac series are being proposed as new soil units in northwestern Iowa. From a pedologic point of view,

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the sola are so similar, so far as is known, that there is no justification for recognizing the two series. The depth to the underlying strata is an important factor, however, in selecting agricultural practices for management of soil and water resources. If the loess is only 30 inches thick, the soil has not enough storage capacity for the precipitation falling in a level terrace channel. If the loess thickness is about 60 inches, it is possible to use level terraces (10). In either case, the solum, about the upper 30 inches, is formed in loess.

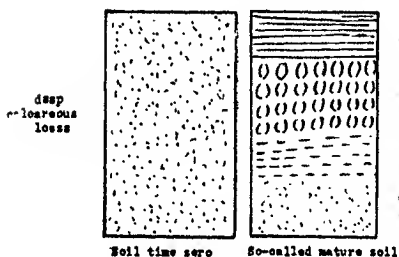


FIG. 1

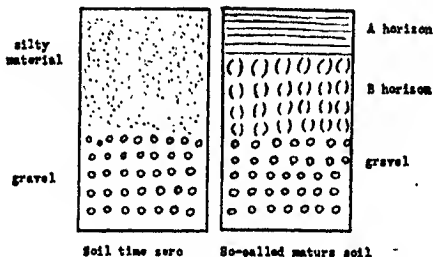


FIG. 2

FIG. 1. POSSIBLE HORIZON SEQUENCE IF SOIL PROFILE UNIT IS FORMED FROM DEEP VERTICALLY UNIFORM PARENT MATERIAL

FIG. 2. POSSIBLE HORIZON SEQUENCE IF SOIL PROFILE UNIT IS FORMED FROM VERTICALLY HETEROGENEOUS PARENT MATERIAL

TABLE 1

*Importance of character of stratum below solum*

SERIES	TYPE	PARENT MATERIAL OF SOLEM	IMPORTANT SOIL PROFILE FEATURES
Galva*	Silt loam	Loess	Dark brown A layer; yellow-brown B layer; loess is present in layers below B layer
Sac.....	Silt loam	Loess	Dark brown A layer; yellow-brown B layer; medium plastic Iowan till is present at about 25 to 40 inches in the profile.

\* Level terraces will generally be satisfactory on Galva soils, but are not safe on the Sac soils.

Figure 3 illustrates how the creation of soil units is strongly biased by assumption of what is relevant to agriculture. Figure 3a is the soil map, made in 1904 (6), of a 640-acre tract of land in Story County, Iowa. The units recognized as significant at that time are essentially an image of the state of knowledge of soil science of that period. Figure 3b shows the soil map of the same tract of land made in 1936 (7). The units recognized in this later map again are an image of the state of knowledge of that period. Figure 4 is an aerial photograph of the same tract of land. At present, additional units would be recognized on a soil map, reflecting a further advance since 1936 in the knowledge of soil science. One might raise the question whether after another period of years, equally significant changes in the classification of soils of this tract of land will follow. It

is conceivable, of course, that a classification at some future date might become simpler if the agricultural needs point to a more extensive rather than a more

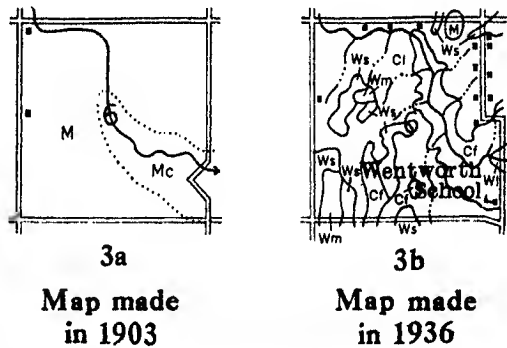


FIG. 3. COMPARISON OF SOIL MAPS OF SECTION 6, WASHINGTON TOWNSHIP, STORY COUNTY, IOWA

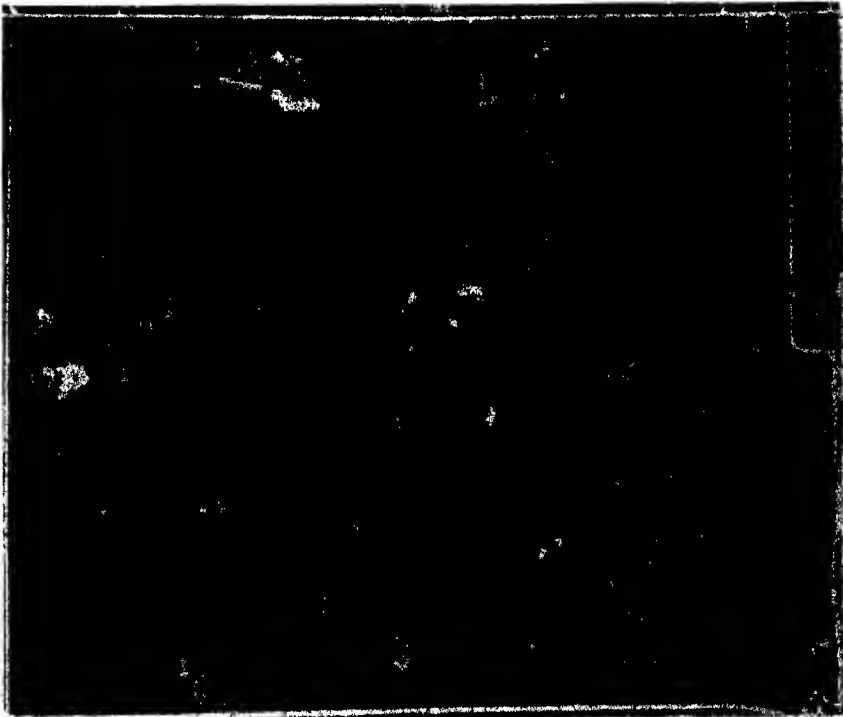


FIG. 4. AERIAL PHOTOGRAPH OF SECTION 6, WASHINGTON TOWNSHIP, STORY COUNTY, IOWA

intensive agriculture. In that case, the data of soil science might be greater than are needed for predicting proper utilization of the soils.

Defining the soil unit involves determination of (a) the geographic dimensions on the landscape which the soil is to occupy, and (b) the range the soil unit is to

be allowed in the soil profile features listed by Marbut (5). It is worthwhile to examine briefly each of these problems, and to look at some of the steps involved in the creation of the soil units.

Figure 5 shows a hypothetical landscape in the deep loess area adjacent to Missouri River in western Iowa. In this area, the over-all climatic features are homogeneous, but the microclimatic variations are probably great because of extreme differences in slope gradient and shape of slope. The biotic factors of soil formation, especially vegetation, seem uniform. Likewise, parent material is essentially uniform vertically and horizontally. Imagine now that the soil scientist begins to study and classify the soils of this area. He will examine soil

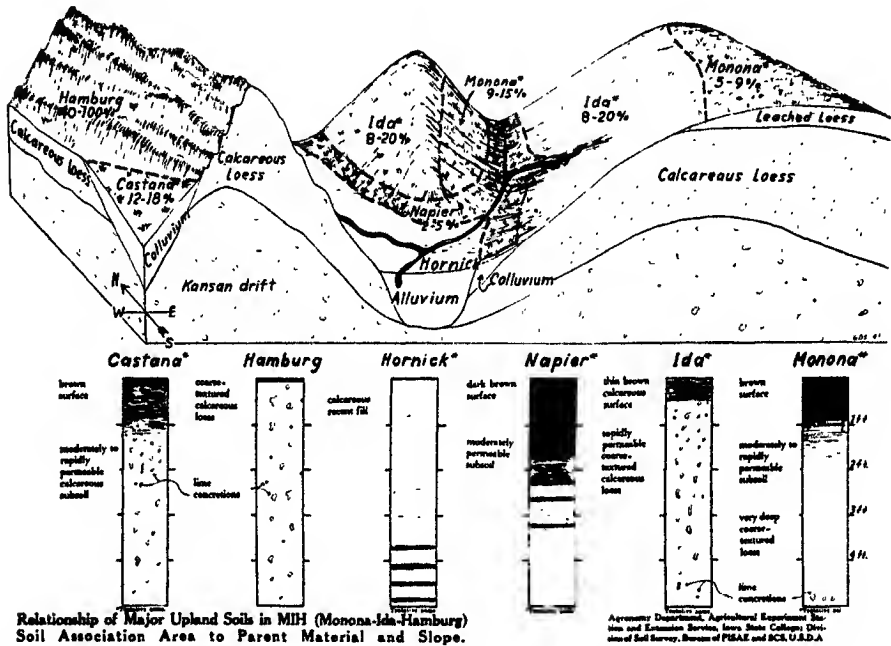


FIG. 5. HYPOTHETICAL LANDSCAPE ILLUSTRATING ASSOCIATION AND OCCURRENCE OF SOIL PROFILE UNITS IN THE DEEP LOESS AREA OF WESTERN IOWA

profiles at many sites. If the sites differ principally in slope, including gradient, aspect, and shape, a functional relationship may be discovered between some soil property or properties and this soil-forming factor.

If the purpose of the study is to make a soil map, the decisive part of the task of the soil scientist has yet to be completed. He has to decide upon the number of soil profile units that need to be recognized for the area. He will have to determine whether the units can be consistently identified and whether boundaries between them can be placed on a map. As discussed previously, permissible variations and inclusions within boundaries on the map will have a strong practical bias. The soil profile units which have actually been recognized in this area are given in figure 5.

The greater the body of knowledge about soil profiles of an area and the more

complete the understanding of the functional relationship of the important soil properties to the soil-forming factors, the easier will be the task of establishing the basic soil profile units of the area. Moreover, the decisions will be more satisfactory if the management requirements are known through research and experience. But the soil scientist is usually not fortunate enough to have all the needed information beforehand. Because he frequently has to proceed without necessary information, the resultant soil maps are often less useful than they might be as soon as the information is obtained. Usually this deficiency arises because the body of knowledge of soil science is inadequate. In most cases the job of soil classification and mapping is one of adding to rather than of "inventorying" the known facts of the area. In other words, it is primarily a part of a fact-finding or research job, and practical aspects are a by-product of the main effort. In other cases, the facts relating to soil management are inadequate. Good examples are the lack of data on soil and water conservation practices and principles, as well as on the significance of these practices to various soil conditions. Currently much stress is placed on showing slope phases and erosion conditions; however, prior to the gathering of factual data on soil erosion, the soil scientist is reluctant to devote much time to delineating detailed slope classes if their relevance is not known.

#### THE CONCEPT OF SOIL SERIES

*Soil series* is defined as follows: "A group of soils having genetic horizons similar as to differentiating characteristics and arrangement in the soil profile, except for the texture of the surface soil, and developed from a particular type of parent material" (1). The soil series must not only have definite soil profile features, but also must occupy an area on the landscape.

Where agriculture is intensive and/or where the soil management practices are very specific, the need is for precise definition of series according to relevant properties. The case of the adoption of level or drain terraces is an example of this need (10). Where agriculture is extensive and the practices become generalized and less specific, the series is often permitted to have a wider range in properties (8). In each case the soil profiles are the fundamental units of observation both in the landscape site and in the study and examination of the continuum of soils of the area.

The current concept of soil series is markedly different from that of earlier years. It will be recalled, for example, that at one time the Marshall series was broader in some respects than even the Prairie great soil group. Through the years, the series has come to mean a landscape unit that has a narrow range of soil properties, most of which are significant to agriculture. It has been possible to develop the series concept only through increases in the basic facts of soil science. It is to be expected that further development and revision of the concept are likely to follow as additional knowledge is gained. In summary, the series is a unit of soil classification which recognizes the maximum number of fundamental features of the soil profile. Hypothetically, the series is the largest landscape unit and also the highest categorical unit of classification about which all features and properties relevant to soil formation are distinguished.

## THE SOIL TYPE

Texture of the surface or plow layer is the basis for differentiating series into types. Current usage of the type is considerably changed from earlier periods. In most instances the series is now subdivided into only a few types, as contrasted to former subdivision into the whole range of texture classes—from sand through clay. Many series, particularly those derived from homogeneous parent materials, now have but one type. Where the parent material lacks vertical uniformity, however, several texture classes may be included in a series. In these cases, the recognized types are usually within a limited range of the texture classes. Thus, loamy sand and fine sandy loam types may be recognized for one series, silt loam and silty clay loam types for another, and silty clay and clay types for yet another. By restricting the permissible types of a series to a fairly narrow range of possible texture classes—that is, to the sandy, loamy, or clayey ranges—the importance of texture to soil use is recognized. It is common experience to find that if the series is limited to a narrow range of fundamental features and properties, the number of types is generally few.

With each series divided into only a few types, the earlier great distinction between soil series and soil type as units of classification has largely disappeared. When only one or two types are recognized, the series and type become essentially similar, and where only one type is recognized, the series and type are identical.

## THE SOIL PHASE

The phase is a subdivision of the soil type. Its properties must therefore be within the defined range of the soil type and series. Phases are separated within a soil type on the basis of characteristics which, although significant to use of the soil by man, have little or no significance in the genesis of the soil. Although there has been too little consistency in the past in deciding whether to recognize a phase or establish a new series, such features as variations in slope, degree of erosion, stoniness, and thickness of alluvial deposits have customarily been used to separate phases within a soil type.

The mapping of phases is of great significance to soil use. Whereas small or, in some instances, great differences in slope gradient may influence selection of the soil management practice, these differences in slope gradient may not have resulted in significantly different soil features. The number of slope phases varies from one series to another, depending on soil profile properties as well as on the character of the climate and present and intended use of the soil. Nomenclature of slope phases has been a problem. Abstract names for different classes of slope gradients have been used in most instances. In general, however, use of names such as *undulating*, *rolling*, and *steep* is not wholly satisfactory because the same gradient limits are not everywhere desirable. Present trends are to use numerical limits for the various phases, such limits being determined according to the series.

Productivity of the soil, its economic valuation, or its management may be affected by degree of stoniness or by severity of erosion. Several degrees of

stoniness or of severity of erosion are often recognized, with the actual definition of each class varying according to local needs and according to the series.

Other phases of types are sometimes mapped. In some instances degrees of salinity are recognized. In certain areas, wet or flooded phases of types are useful for special purposes.

Incorrect use of the phase occurs when any one of a number of fundamental soil features is used as a basis for creating an "aberrant" phase. Frequently, these kinds of phases have been shown on published maps, and in most cases, they have been established subsequently as new series. As this procedure is useful as an interim kind of nomenclature, there is need for recognizing an aberrant of the archetype. It does not seem logical or consistent that in one instance, the term *phase* should be used to designate a property which lies within the defined range of the type and, in another instance, a property which lies outside the defined range should be used to designate the "aberrant" soil. Use of the term *phase* should be limited, therefore, to features, such as slope, erosion, and stoniness, which lie within the range of the type. A new term should be employed for the aberrant from the archetype. It has been suggested that the term *variant* be used to designate the latter. For example, the Prairie series derived from a parent drift which is more slowly permeable or plastic than usual for the Carrington series could be designated as the "Carrington, plastic till variant." If the variant soil is extensive, a new series could be established at a later date.

#### THE FAMILY CATEGORY OF SOILS

The current concept of the family category is essentially as defined by Baldwin *et al.* (1). These authors view the family as a category of soils intermediate between the great soil group and the series categories. The concept of the family category held by Shaw has not been generally accepted although it is of importance in genetic groupings. In the scheme of soil classification presented by Marbut (5), the so-called "immature" or "abnormal" soils were not considered in the categories higher than the family. Baldwin, Kellogg and Thorp, (1), in their modification of the system proposed by Marbut provided for the so-called "imperfectly" developed soils at the great soil group and higher levels. This change was an important step forward in developing a natural system of soil classification, for it meant that, starting with the lower units, all soils could be arranged into successively higher categories.

Usually two or more geographically separated series are included in a family of soils, and therefore the family is not likely to be useful in attempts to reduce cartographic detail. For this latter purpose, the catena, complex, or association is commonly used if geographic units of greater heterogeneity than the type are to be shown on small-scale maps.

At present there is little published material suitable for guidance in the grouping of series into families. Brown and Thorp have published a description of the Miami family (2), and little can be added to their discussion on the family category. Current efforts by workers in soil classification to group series into

families will likely result in appearance of more information in the literature in the next few years.

As the family category is intermediate in generalization between the great soil group and the series, it is obvious that the number of fundamental soil profile features used will be intermediate. For the great soil group, a particular horizon may have considerable range in one or more parameters. For example, the thickness and color of the A horizons of the Prairie soils may range widely. In any series of Prairie soils, the range is rather narrow if eroded phases are excluded. In the family differentiation, the range in color and thickness of the A horizon may be but little greater than for the series, but if so, other parameters must be permitted to have a wider range. Parent material of soils in a family must be

TABLE 2  
*Some Prairie soil series grouped into families*

FAMILY	SERIES	PRINCIPAL SOIL PROFILE FEATURES	
		Parent Material	Horizon Features
Muscatine	Muscatine	Loess	A horizons very dark brown, about 16 inches thick; B horizons slightly mottled; permeability moderate; mottling due to intermittent high water table.
	Brenton	Glacial outwash	
	Mahaska	Loess	
Tama	Tama	Loess	A horizons dark grayish brown, about 12 inches thick; B horizons yellowish brown; permeability moderate; good oxidation due to topographic position and permeable B horizon.
	Otley	Loess	
	Saybrook	Till	
Grundy	Grundy	Loess	A horizons dark grayish brown, about 12 inches thick; B horizons medium to highly mottled; permeability slow to very slow because of genetically developed B horizons.
	Seymour	Loess	
	Lagonda	Till	

permitted to have considerably wider range than in a series, although extreme ranges can not be permitted. Parent material differences may be in physical, mechanical, or mineralogical characteristics. It is also likely that color, which may reflect organic matter content as well as internal natural aeration conditions, will be of considerable importance in grouping Prairie soils into families. In table 2 are given some examples of family groups of Prairie soil series. The Muscatine family is differentiated from the Tama family mainly by color and thickness of the A horizon and by color of the B horizon. The members of the Muscatine family are less well aerated than are the members of the Tama family. The Grundy family, which occupies similar topographic positions to the Tama family, has oxidation features like the Muscatine family. The members of the Grundy family have slowly permeable genetic B horizons. As aeration conditions are less favorable than for the Tama family, the B horizons of the Grundy family are mottled in color.



An additional problem in the study and grouping of series into family units is that of nomenclature. The series name is, of course, abstract, but the great group name is connotative in many instances. Few soil scientists will attempt to become familiar with all or even a large part of the known series. If the name of a series is used to designate the family, then frequently the family will have as little meaning as the unfamiliar series. Use of connotative names, on the other hand, will certainly involve difficulties because of the large number of names required. It would seem that the family category is necessary to a natural system of classification, but statements about use of this category must await development of family groupings.

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# HIGHER CATEGORIES OF SOIL CLASSIFICATION: ORDER, SUBORDER, AND GREAT SOIL GROUPS

JAMES THORP AND GUY D. SMITH<sup>1</sup>

The taxonomy of soils presented in "Soils and Men" (1) has undergone continuous study in the Division of Soil Survey with the purpose of making improvements. Many changes have been suggested and discussed by the various members of the staff. A few changes have met with general but not unanimous approval of the staff and have been incorporated into the classification as follows:

1. The distinction between Pedalfers and Pedocals in the zonal order no longer appears in the classification table.
2. New great soil groups known as Gray Wooded or Gray Podzolic soils, Low-Humic Glei soils, and Regosols have been established.
3. Dry Sands, Yellowish-Brown Lateritic, and Yellow Podzolic soils have been included with other great soil groups.
4. Changes in nomenclature and minor modifications in definitions have been made in a few great soil groups. A number of other proposed changes are undergoing study.

The classification presented in table 1 is not considered to be approaching a static condition.

Following in alphabetical order are brief definitions of most of the newly recognized or modified great soil groups and a short discussion of each:

*Ando soils*<sup>2</sup> (not listed in table of classification). The *Ando soils* are given a tentative name, coined from the Japanese language, which means *dark soils*. These soils have developed very widely in deposits of volcanic ash in the Japanese islands from Hokkaido in the north to Kyushu in the south, in the Philippines, in Hawaii, and almost certainly in other Pacific islands, in Africa, and in Central America. They consist, primarily, of a dark-brown to black A<sub>1</sub> horizon, averaging about 1 foot thick, of fine-crumb or granular structure with an organic content ranging up to 30 per cent in the darkest members of the group. The average organic content is close to 8 per cent in the A horizon for the group as a whole. Some members of the group as now recognized have distinct B horizons with more clay than A horizons, but the younger members are essentially "A C soils." The soils range from strongly to slightly acid in reaction and generally have low exchangeable divalent bases and high exchangeable alumina. SiO<sub>2</sub>/R<sub>2</sub>O<sub>3</sub> ratios in most of these soils in Japan are less than 2, although they are higher in some of the younger soils.

The Ando soils occur in humid to perhumid climates with temperature efficiency ranging from cool mesothermal to tropical (8). Natural vegetation varies from place to place and includes broad-leaved and coniferous forest types with, in many places but not everywhere, an understory of bamboo.

The Division of Soil Survey has not reached a decision as to whether the Ando soils should be grouped with the Brown Forest soils or be recognized as a new great soil group.

*Gray Wooded soils (Gray Podzolic soils)*. A subcommittee of the Division of Soil Survey

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<sup>2</sup> Notes on Ando soils were obtained by James Thorp in the field and in conference with Japanese soil scientists in Japan, 1945, when the reconnaissance soil survey of Japan was initiated by the Natural Resources Section, Supreme Command Allied Powers, and from W. S. Ligon and party in 1946-47 during the progress of the survey.

**TABLE 1**  
*Soil classification in the higher categories*

ORDER	SUBORDER	GREAT SOIL GROUPS
Zonal soils	1. Soils of the cold zone 2. Light-colored soils of arid regions  3. Dark-colored soils of semiarid, subhumid and humid grasslands  4. Soils of the forest-grassland transition  5. Light-colored podzolized soils of the timbered regions  6. Lateritic soils of forested warm-temperate and tropical regions	Tundra soils Desert soils Red desert soils Sierozem Brown soils Reddish-Brown soils Chestnut soils Reddish Chestnut soils Chernozem soils Prairie soils Reddish Prairie soils Degraded Chernozem Noncalcic Brown or Shantung Brown soils Podzol soils Gray wooded, or Gray Podzolic soils* Brown Podzolic soils Gray-Brown Podzolic soils Red-Yellow Podzolic soils* Reddish-Brown Lateritic soils* Yellowish-Brown Lateritic soils Laterite soils*
Intrazonal soils	1. Halomorphic (saline and alkali) soils of imperfectly drained arid regions and littoral deposits  2. Hydromorphic soils of marshes, swamps, seep areas, and flats      3. Calcimorphic soils	Solonchak, or Saline soils Solonetz soils Soloth soils Humic-Glei soils* (includes Wiesenboden) Alpine Meadow soils Bog soils Half-Bog soils Low-Humic Glei* soils Planosols Ground-Water Podzol soils Ground-Water Laterite soils Brown Forest soils (Braunerde) Rendzina soils
Azonal soils		Lithosols Regosols (includes Dry Sands) Alluvial soils

\* New or recently modified great soil groups.

work-planning conference, March 1948, offered approximately the following definition of Gray Wooded soils: This is a group of well-developed, well-drained soils having a moderately thin duff (A<sub>e</sub>) horizon and a thin organic-mineral (A<sub>1</sub>) horizon, over a light-colored

bleached ( $A_1$ ) horizon, over a brown more clayey, blocky or nuciform ( $B_1$ ) horizon, grading below into lighter-colored, more friable ( $B_2$  and C) horizons.

Gray Wooded soils of western Canada and United States occur in subhumid to semiarid cool mesothermal to microthermal climatic regions under coniferous, deciduous, or mixed forest cover. Color profiles resemble those of Podzols, but  $A_1$  horizons average about twice as thick as those of most Podzols in North America. B horizons of Gray Wooded soils are generally lower in chroma than those of Podzols. Gray-Wooded soils developed in calcareous materials range in reaction from neutral to medium acid, and many of them have horizons of calcium carbonate accumulation below the  $B_2$  horizon. Strongly acid reactions are exceptional. They differ from the Gray-Brown Podzolic soils in having grayer and lighter-colored  $A_1$  horizons and generally a less acid reaction.

The Gray Wooded soils appear to be correlatives of the Gray Forest soils of Russia, and they occupy a similar position between the Podzols of more humid regions and the Chernozems of regions where effective moisture generally is somewhat less. These soils are described in detail in publications of Manitoba, Saskatchewan, and Alberta (2, 5, 6).

*Humic-Glei soils.* At the work-planning conference, it was agreed that the Wiesenboden and those soils, formerly grouped with Half-Bog soils, that lack a muck or peat  $A_0$  horizon should be combined as one great soil group and be given a new name. Of the several names suggested, *Humic-Glei soils* received the fewest objections. That name is used provisionally in this paper.

A subcommittee offered approximately the following definition for this group: An intrazonal group of poorly to very poorly drained hydromorphic soils with dark-colored organomineral horizons of moderate thickness underlain by mineral glei horizons . . .

Humic-Glei soils occur naturally under either swamp-forest or herbaceous marsh vegetation mostly in humid and subhumid climates of greatly varying thermal efficiency. A large proportion of Humic-Glei soils range from medium acid to mildly alkaline in reaction. Few are strongly acid.

*Laterite soils.* The work-planning conference agreed to abandon the term *Laterite soils*, as defined in "Soils and Men," and to substitute a new term, not yet selected. Two terms suggested at the conference are *Latosol* and *Chromosol*. This great group of soils includes the more friable and ferruginous of the "red loams" of European, Asiatic, and Australian literature. It may be synonymous with Marbut's "Ferruginous Laterite soils" (4, p. 157).

*Lithosols* may be defined as follows: An azonal group of soils having an incomplete solum or no clearly expressed soil morphology and consisting of a freshly and imperfectly weathered mass of hard rock or hard rock fragments; largely confined to steeply sloping land.

The original intent of the definition of *Lithosols* in "Soils and Men" was to include only weakly developed, very stony soils or situations in which the solum and/or regolith occurs as a shallow accumulation over consolidated rock. For a time, azonal soils developed in unconsolidated rock, such as loess, were included with *Lithosols*, but are now classed provisionally as *Regosols*.

*Low-Humic Glei soils.* The work-planning conference agreed that a new great soil group was needed to cover imperfectly drained to poorly drained soils that do not fit well into any of the various *Planosols* or into the *Humic-Glei soils*. The conference objected less to the name *Low-Humic Glei soils* than to other names proposed. That name is used provisionally here.

A subcommittee offered approximately the following definition for this group: An intrazonal group of imperfectly to poorly drained soils with very thin surface horizons, moderately high in organic matter, over mottled gray and brown glei-like mineral horizons with a low degree of textural differentiation.

*Low-Humic Glei soils* range in texture from sand to clay, and the parent materials vary widely in physical and chemical properties. These soils occur largely under a natural cover of swamp forest, and perhaps of marsh plants in some areas. A large proportion of them range from medium to very strongly acid in reaction. Few are neutral or alkaline.

*Planosols.* At the work-planning conference, the suggestion that *Planosols* be elevated

to the rank of a suborder of intrazonal soils and be broadened to include Ground-Water Podzol soils and Ground-Water Laterite soils was well received but was not unanimously accepted. Planosols are defined provisionally as follows: Intrazonal soils having one or more horizons abruptly separated from and sharply contrasting to an adjacent horizon because of cementation, compaction, or high clay content. They are found under forest or grass vegetation in mesothermal to tropical perhumid to semiarid climates, usually but not always with a fluctuating water table. In many instances the cemented or compacted horizons lie beneath a moderately well or well-developed B horizon that has a higher percentage of clay than the A horizon.

Many soil scientists feel that the current classification does not provide adequately for certain periodically poorly drained soils that have "silt pans," or "hardpans," but have no horizons with high percentage of clay. If Planosols were raised to the level of suborder, they could be permitted to include soils of these kinds as well as "claypan soils." They could also be allowed to include Ground-Water Podzol, Ground-Water Laterite, and Soloth soils, so far as morphology is concerned.

*Red-Yellow Podzolic soils.* A majority of the work-planning conference personnel, as well as many representatives of state soil survey agencies, felt that Red Podzolic and Yellow Podzolic soils belong in one great soil group. The conference agreed to the name *Red-Yellow Podzolic Soils* for this combination.

A subcommittee prepared the following definition for Red-Yellow Podzolic soils: A group of well-developed, well-drained acid soils having thin organic ( $A_0$ ) and organic-mineral ( $A_1$ ) horizons over a light-colored bleached ( $A_2$ ) horizon, over a red, yellowish-red, or yellow and more clayey (B) horizon. Parent materials are all more or less siliceous. Coarse reticulate streaks or mottles of red, yellow, brown, and light gray are characteristic of deep horizons of Red-Yellow Podzolic soils where parent materials are thick.

*Reddish-Brown and Yellowish-Brown Lateritic soils.* In line with the logic followed in combining Red Yellow Podzolic soils as one group, a majority of the work-planning conference preferred to eliminate the Yellowish-Brown Lateritic soil group by combining it with the Reddish-Brown Lateritic group, because structures and chemical characteristics of the two groups are similar in several respects. The whole question of the nomenclature of soils formerly classified as *lateritic* is now under review, and it is expected that new names will be proposed to take the places of the *Laterite soils*, the *Reddish-Brown Lateritic soils*, and the *Yellowish-Brown Lateritic soils* of the 1938 Yearbook classification. Among terms proposed are *Reddish-Brown Latosols* and *Reddish-Brown Chromosols*. None of these soils has the podzolic morphology, with light-grayish  $A_2$  horizons, characteristic of the geographically associated Red-Yellow Podzolic soils developed in siliceous parent materials. A few other groups of soils with free oxides of iron and aluminum are known and eventually will be given new names.

*Regosols* may be defined as follows: An azonal group of soils consisting of deep unconsolidated rock (soft mineral deposits) in which few or no clearly expressed soil characteristics have developed; largely confined to recent sand dunes, and to loess and glacial drift of steeply sloping lands.

Soon after the definition of *Lithosols* was published in the 1938 Yearbook, it was realized that many weakly developed soils occur in deep soft-rock deposits, like loess and sand, that are not *stony* in the ordinary sense of the word. These nonstony soils were called *Lithosols* for a time, but a practical need was felt for distinguishing deep soft soil materials from very stony ones. Hence the proposal of the name *Regosol*. This new term is not yet fully established in the literature, and it may prove desirable eventually to give the concept some other status than that of a great soil group.

#### THE SOIL ORDERS

Although a natural classification of soils should be based on physical and chemical properties of the soils themselves, it is difficult to adhere strictly to

morphology. Whether we like it or not, we are influenced by geographic considerations and by a multitude of hypotheses of soil genesis, some well substantiated and others with obvious flaws. The taxonomy presented above is based to a considerable extent upon the concept of a normal or zonal soil. Soils are classified according to the relationships of their profile characteristics to the characteristics of the zonal soil.

*An appraisal of the concept of zonality in soils*

It is well established that definite relationships exist between soils and the biotic and climatic environments under which they have developed where sufficient time has elapsed for these factors to be effective. Differentiation of soil horizons and development of distinctive soil profiles seem to be fairly rapid on freshly exposed parent materials, but with time the rate of development slows down. Eventually, the rate of change is so slow that an apparent, but probably not real, state of equilibrium is reached between accumulation and destruction of organic matter. Soil structure and texture differentiation seem to reach their optimum expression and to change but little over a long period. This is the stage of profile development frequently referred to as *maturity*. At this stage many soils on different kinds of parent materials, but with similar vegetation, drainage, and climatic conditions, take on many common characteristics. Of the so-called mature soils, those with naturally good, but not excessive drainage, have been placed in an order of *zonal soils*. Their physical and, to a certain extent, their chemical characteristics are a reflection of the climatic and ecological zone in which they occur.

Zonal soils, in general, are characterized by well-differentiated horizons and by profiles that differ markedly according to the climatic-ecological zone within which they occur. The term *normal soils* as applied by Marbut (4, p. 149) and others is a synonym for *zonal soils*. Objection has been raised to the term *normal* in recent years because it implies that other soils are either abnormal or sub-normal. In a narrow sense, this implication is valid, insofar as young soils have few true soil characteristics, and old soils or soils with poor or intermittently poor drainage have additional horizons, or horizons that are developed beyond the state characteristic of the associated zonal or normal soils. In a broader sense, virtually all soils are normal in relation to the summation of the factors that have caused their development. We can find more justification for the term *zonal soil*, therefore, than we can for the term *normal soil*.

It is a matter of observation that each of the zonal soils is developed most characteristically within a certain range of climatic and ecological conditions, but it is also true that each of many zonal soils, for example, those of the Gray-Brown Podzolic group, not only have a characteristic climatic-ecologic zone of occurrence, but may also be found in quite different climatic and ecologic environments where their presence can be explained by some other factor of soil formation, like time or parent rock. For example, the presence of soils morphologically like Gray-Brown Podzolic soils in the hot, humid forested lowlands of Puerto Rico (7) and Assam, where one would expect to find Red-Yellow Podzolic



soils, is thought to be the result of the relative youth of the soils and perhaps of certain kinds of parent materials that are not so easily converted to Red-Yellow Podzolic soils as are others. In time, these soils, classed provisionally as Gray-Brown Podzolic, probably will be converted to other great groups.

Reddish-Brown Lateritic soils, or at least soils that resemble them, characteristic of humid tropical climates like those in Puerto Rico, the Philippines, Africa, south China, and Malaya also occur as far north in the United States as central Virginia and western Washington, and as far north as the Yangtze Valley of central China. The Davidson soils of Virginia and the Aiken soils of Oregon are typical examples. The presence of such soils in temperate northern regions may be due at least partly to the fact that these soils have been exposed to essentially similar, but perhaps somewhat less intensive, soil-forming processes for a much longer time than the Gray-Brown Podzolic soils have been developing in Puerto Rico and Assam. It is also true that the soils in Virginia and Oregon closely resembling the Reddish-Brown Lateritic soils, are developed from kinds of dark igneous rocks that lend themselves especially well to the formation of these soils. Furthermore, these soils in Virginia and Oregon probably have been developing since middle or early Pleistocene time and, therefore, not only are old, but also have been subjected to a number of changes in climatic conditions with probable changes in types of vegetation. We may reasonably suggest, therefore, that existing soil characteristics may be due in part to environmental conditions that no longer exist.

However the matter may be explained, the fact remains that there is a very definite overlap of soils commonly associated with tropical climates and those associated with cooler climates. Soil scientists are so accustomed to finding soils of certain great soil groups within a limited climatic environment that some are inclined to overlook this overlap. When we classify soils according to their characteristics, the present writers feel that climatic environment, although relevant, should not be considered strictly as a soil characteristic. Greatest emphasis in soil classification should be given to the profile characteristics of soils themselves. Even then, plenty of geographic and genetic bias will remain in our classification.

Though it is possible for a genetic bias to be too strong for a natural classification, it is neither possible nor desirable to eliminate genetic considerations completely from our classification. It will always be necessary to examine the soil critically from a genetic point of view to determine which properties are genetic and which are accidental. The question of whether a given property was developed or inherited from a parent material must be answered before the classification can have validity. For example, laterite horizons are an essential feature of the Ground-Water Laterite soils. All soils of this great soil group must have a laterite horizon. Nevertheless, not all soils having a laterite horizon will be Ground-Water Laterite soils. The laterite layer may be a relict inherited from an earlier soil. In this case the laterite must be considered as part of the parent material and not as soil horizon. Soils developed from anisotropic parent materials will frequently give great trouble in classification if genetic factors are eliminated from consideration.

*Zonal soils versus soil zones*

Since it is true that certain zonal soils are developed most characteristically within a limited range of climatic and ecologic conditions, it has been customary to give each soil zone the name of the appropriate zonal soil. For example, we speak of *Podzol soil* as a normal zonal great soil group. In the Podzol zone are many different kinds of zonal, intrazonal, and azonal soils, some of which are closely related in parent material and utterly different in profile characteristics. There is little likelihood that a zonal Podzol profile will ever be confused with a clear-cut example of intrazonal Half-Bog soil that may occur within 50 feet of the Podzol profile. As with the Podzol soil, the Half-Bog soil may be explained partly by its climatic environment and the type of vegetation; but its major properties must be explained on some other basis, usually that of drainage condition which controls the amount of effective moisture.

*Intrazonal and azonal soils*

Intrazonal soils commonly have many of the characteristics of the associated zonal soils. For example, the Wiesenboden (Humic-Glei) soils have much in common with the Prairie and Chernozem soils; the Solonetz soils of the Brown soils zone resemble normal Brown soils in some respects more than they do the Solonetz soils of the Chernozem zone. The Planosols of Tennessee and Georgia have many characteristics common to the zonal Red-Yellow Podzolic soils formed from the same parent materials. To this extent, certain intrazonal soils are as *zonal* as the associated normal zonal soils.

Azonal soils are those in which profile development is at a minimum or near minimum. It is almost impossible to find a definite natural line where soils cease to be azonal and begin to be zonal or intrazonal. We can define the modal condition, but we cannot draw sharp lines to circumscribe limits of the order. Soils begin to be azonal just beyond Jenny's zero point of soil formation (3, p. 53), and they cease to be azonal at an arbitrary stage of development when zonal or intrazonal characteristics become unmistakably evident. Virtually all azonal soils reflect to a minor degree effects of environment. For example, azonal soils in the Chernozem zone, developed under grass, have thin A<sub>1</sub> horizons that are slightly darker than the parent material immediately beneath. To the degree that the A<sub>1</sub> horizon has the structure and color characteristics of adjacent Chernozem soils, we might think of the soil as a chernozemic Lithosol or Regosol. Similarly, some Lithosols are weakly podzolized, and others are salinized.

The difficulty in placing the *Ando soils* in the current scheme of classification illustrates one of the defects of a genetic system. These soils apparently have developed for the most part in volcanic ash, under a forest vegetation, and in a humid to perhumid mesothermal to tropical climate. If the fibrous root system of the vegetation is the factor responsible for their high content of organic matter and dark color, they are zonal soils reflecting the influence of climate and vegetation and should be placed in the same suborder with Prairie soils. Yet, they would hardly belong in the suborder called *dark-colored soils of the semiarid, subhumid, and humid grasslands*. If the parent material is the cause of the dark color, they belong in the intrazonal order, where they require a new suborder.

Thus, it will be seen that, with a genetic system of classification, soils whose genesis is imperfectly understood cannot be placed in their proper position. Likewise, if the genetic bias in a system is too strong, soils cannot be classified until their genesis is understood.

The concept of zonality, intrazonality, and azonality would seem, then, to suffer from major weaknesses. First, the genetic bias is very strong. The zonal and intrazonal orders can be defined only in genetic terms. The authors are unable to discover any mutually exclusive characteristics of these two orders. The azonal order, in contrast, is defined in terms of soil characteristics. Second, the concept that any given group of zonal soils is found in a single climatic and biotic zone has many exceptions. Third, some of the intrazonal and azonal soils show many zonal characteristics.

Nevertheless, the orders, though not *natural* orders, serve the purposes of a *natural* system of classification in that they show relationships, and they aid in remembering characteristics. The system would, however, be more useful if the orders could be defined in terms of soil characteristics.

#### THE SOIL SUBORDERS

The suborders presented in the foregoing classification, like the orders, are defined both in terms of soil characteristics and in genetic terms. The suborders of zonal soils are described for the most part in terms of soil characteristics, for example, *light-colored podzolized soils of the timbered regions*, even though the genetic bias is strong.

Most suborders of intrazonal soils consist of great soil groups having one or more important features in common, even though the names imply genesis. The inclusion of calcimorphic soils in the intrazonal order can be criticized in a natural classification on the ground that these soils have much more in common with the zonal soils, particularly the dark-colored soils of the semiarid, subhumid, and humid grasslands, than with any of the other suborders of intrazonal soils. The calcimorphic soils cannot be grouped with the zonal soils if the organic content is thought to be the result of parent material rather than of climate and vegetation. An even stronger case could be made for calling the Podzol soils with ortstein horizons *intrazonal*, because they can only be found in sandy parent materials.

The hydromorphic soils at present are perhaps the most heterogeneous of the suborders. Though most hydromorphic soils show evidences of permanent or periodic excessive moisture, some of the Planosols with iron and silica pans, such as the Rocklin soils of California, have well-oxidized reddish A and B horizons overlying the hardpan. If such soils are occasionally saturated with water, the intervals are too short or too infrequent to produce significant reducing conditions in the solum. It is difficult to see justification for including well-oxidized soils with the hydromorphic suborder. Some revision of the hydromorphic soils would appear necessary for a natural classification.

#### THE GREAT SOIL GROUPS

The great soil group category has proved the most useful of the higher categories, perhaps because it is possible to make more numerous specific statements

about the various great soil groups than about the higher categories. The genetic bias, so strong in the order category, has been held to reasonable limits in the great soil group category even though some of the names carry strong genetic implications, for example, *Prairie soils*.

The great soil groups will undergo modifications as our knowledge of soils increases. Some of the currently recognized great soil groups may be combined and new groups will undoubtedly be established. As the detailed study of soils is extended in tropical and arctic regions, considerable modification may be expected. Even at present, a number of soils are known to occur which have not been placed satisfactorily in any existing great soil group. Among these are the following:

1. The Ando soils, briefly described on foregoing pages.
2. The "Black Cotton soils" of India (Regur).
3. The Shachiang and "Lakeland Shachiang" soils of China.
4. Some of the "caliche soils" of western North America, some of which are like the Shachiang soils of China.
5. Some of the "black tropical soils" and "black-over-red tropical soils" known in the Philippines, West Indies, South America, and Africa.

#### CONSTRUCTIVE SUGGESTIONS ON CLASSIFICATION

It is hoped that terms indicating zonality or lack of it may be abandoned eventually in favor of terms based on soil characteristics. Work in the Division of Soil Survey and among state cooperators has not yet advanced sufficiently to permit presentation of a completely revised system of classification that will be satisfactory to all concerned.

It seems clear that if the classification based on the concept of zonality is to be abandoned in favor of one based more largely on characteristics, at least three, instead of two, categories will be needed above the category of great soil group.

Since each of the suborders now consists of great soil groups having fundamental features in common, few changes are needed. Some rearrangement of the suborders will be necessary if the orders are to have mutually exclusive common characteristics. For example, when the genetic bias is reduced, it is seen that the calcimorphic soils have so many properties in common with the Chernozem and Prairie soils that it is difficult to justify separate suborders. The suborders need to be given names if the category is to be useful, and it is felt that the names should be connotative.

There is also a possible need for an additional category between the great soil group and family categories to bridge the wide gap that now exists.

Within each great soil group are differences in profile characteristics which can be interpreted as different stages of development. These characteristics necessarily vary with the great soil group, but within each great group they must be considered as one of the bases for further subdivision. Members of a great soil group whose characteristics are weakly developed for the group could be considered *minimal* members of that group. Members whose characteristics are developed beyond the median for the group could be considered *maximal*. Other members would then be considered *medial*. The need for such a category, or lack of it, will become more apparent as attempts are made to develop family groupings of soils.

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## INTERPRETIVE SOIL CLASSIFICATION: RELATION TO PURPOSE

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Soils may be classified not only in terms of their own characteristics, but in terms of their behavior or capabilities. Interpretive soil classification is the process of grouping soils into classes made to show predictions of their behavior or capabilities, or other things about them that are inferred from their characteristics.

Interpretive soil classifications may be designed to serve many purposes and may take many forms. The four papers following deal with some of them. When soils are grouped according to the factors of soil genesis, as discussed in the first of the four papers, the classification is, of course, interpretive. Its purpose is to improve our understanding of the processes that give soils their characteristics.

Other kinds of interpretive soil classifications are designed to show the predicted results of using or treating soils in specified ways. Their purpose is to help people make good decisions in use and treatment of soils. Most persons do not have available results of all the accumulated experience and observations which tell us what to expect when we use or treat a soil in a particular way. Unless this experience can be summarized and brought to their attention in the form of predictions for different kinds (classes) of soil, the results of using or treating a soil in a particular way must be determined by trial and error in every single place.

We may classify soils according to expectable yield under specified management.<sup>2</sup> We may classify them according to predicted success of tung nuts, hemp, castor beans, or peanuts;<sup>3</sup> according to suggested crop rotations;<sup>4</sup> according to lime requirement;<sup>4</sup> according to measures for erosion control;<sup>4</sup> according to need of drainage, and so on. We may classify them according to methods of treatment required to prepare them for highway or airport construction, or according to suitable methods of drainage or irrigation. We may classify them according to physical properties such as compressibility, bearing capacity, stability, elasticity, permeability,<sup>4</sup> infiltration capacity, and moisture-storing capacity, in order to predict their behavior under given conditions.

We distinguish between classifications to show those features of behavior, such as compressibility, moisture-storage capacity, or productivity, that result

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<sup>2</sup> For an example see Smith, G. D., Riecken, F. F., and Smith, R. S. Cass County Soils. *Ill. Agr. Exp. Sta. Soil Rpt.* 71: 7, 1947.

<sup>3</sup> For examples see Bachman, K. L., Crowe, G. B., and Goodman, K. V. Peanuts in Southern Agriculture, pp. 103-106. U. S. Department of Agriculture, 1947. Also Peterson M. J., et al. Sweet potato production in South Carolina. *S. C. Agr. Exp. Sta. Bul.* 364 app. table 1, 1946.

<sup>4</sup> For example see Smith, G. D., Riecken, F. F., and Smith, R. S. Cass County soils. *Ill. Agr. Exp. Sta. Soil Rpt.* 71: 11, 12, 17, 1947.

from characteristics of the soil, and those made in terms of single soil characteristics, such as texture, stoniness, depth, or slope. The former are interpretive soil classifications. The latter are more properly regarded as special classifications designed to show differences among soils in individual, directly observed characteristics.

We may make these interpretive soil classifications only when trials, tests, and observations of behavior on the different kinds of soil have supplied enough evidence to warrant classification.

Interpretive soil classification must be preceded by the basic soil classification. Otherwise, the interpretive classification would be possible only after trials had been made in every place. The basic soil classification must delimit kinds of soils sufficiently uniform in their characteristics that we can reasonably expect about the same results from a given use or treatment throughout the extent of any one kind.

In the basic soil classification system, the soil type and phase are the most nearly uniform categories and have the narrowest range of characteristics. For this reason they can be grouped into a greater variety of interpretive soil classes than the less uniform members of the higher categories. As we move into the successively higher categories, the variety of predictions that can be made about a member of the category becomes less. For example, we can make fewer interpretive classifications of soil series for practical purposes than we can of soil phases because of variation in slope, stoniness, and texture found within a soil series.

The evidence for interpretive soil classifications is obtained from planned experiments, tests of soil behavior, and observed experience on definite kinds of soil. Each experiment or observation is made on an area of soil so small that geographically it is scarcely more than a point. We must have some means of knowing where else the results are likely to be duplicated. The soil classes of the basic soil classification system, shown on maps, afford such a means. From them, we learn the extent of each kind of soil. By experiments or observations upon each kind we accumulate evidence with which to make predictions for that soil. As evidence is accumulated for different soils we are able to classify the soils with respect to the use or treatment being observed. The evidence may show two or three soils to have nearly the same behavior with respect to a particular use or treatment. These we group together, for the purpose of prediction, into an interpretive group or class of soils.

Within any region are found different kinds of soils, markedly different kinds often occurring in association on a single farm. Farmers use these contrasting soils in complementary fashion to support the combination of enterprises that make up the farm business. Very commonly, several different soils occur associated in a characteristic pattern throughout a region. As we accumulate evidence of the behavior of each, through research or observation of experience, we are enabled to make predictions, not only for the individual soils but for areas of associated soils used in complementary fashion. These predictions



may deal with such things as crop-pasture combinations, combinations of farm enterprises, or sizes of operating units. As evidence accumulates to allow prediction for different areas, these may be classified in terms of differences among them in the predictions made. We should then have an interpretive soil classification in which the units classified are areas of geographically associated soils, rather than individual kinds of soil having uniform characteristics. It is reasoned that within each such area the soil pattern presents a nearly equal opportunity for farms of a given size and organization, provided there are no important differences in market opportunities within the area.



## INTERPRETATIVE SOIL CLASSIFICATIONS: GENETIC GROUPINGS

ERIC WINTERS<sup>1</sup>

The chief purpose of genetic groupings is to relate variation in soil properties to the causative environmental factors. Relationships discovered through the development of genetic groupings may prove important not only to a better understanding of the processes of soil formation, but also to the refinement of some of the taxonomic groups themselves.

The classes in a natural taxonomic grouping consist of soils with *similar* properties, whereas those in a genetic grouping consist of soils with *differences in* properties, assumed to be attributable to differences in one of the environmental factors. As environmental factors frequently vary in a gradual and continuous manner, a similar continuity of variation in soil properties is to be expected. Sometimes this latter continuity of variation tends to be overlooked in taxonomic classification because attention is directed incorrectly to the properties of the average individual of the group. Genetic groupings, however, give emphasis to this continuous and gradual variation.

### KINDS OF GENETIC GROUPINGS

Corresponding to the five factors of soil genesis—relief, time, parent material, climate, and vegetation and associated biologic agents—five major kinds of genetic classifications are recognized. The terms *toposequence*, *chronosequence*, *lithosequence*, *climosequence*, and *biosequence*, respectively, have been suggested by Jenny (8) for each of these.

Most of the factors of genesis are complex. Jenny (8) has suggested that toposequences may include clinosequences (involving only erosion effects) and hydrosequences (involving only drainage effects); climosequences may be subdivided to give thermosequences, hydrosequences, and perhaps others. Because this complexity is not always recognized, difficulties and misunderstandings about genetic groupings frequently arise.

### GENETIC GROUPING ACCORDING TO RELIEF: THE CATENA OR TOPOSEQUENCE

The term *catena* was suggested originally by Milne to designate any soil association underlain by parent rock of uniform character, "the various soils included in a catena corresponding to the links in a hanging chain" (11). Workers in the United States have extended the term *catena* to mean a genetic grouping according to relief, or toposequence. In the Yearbook of Agriculture for 1938 (17), the *catena* is defined as "a group of soils within one zonal region, developed from similar parent material, but differing in characteristics of the solum owing to differences in relief or drainage." Relief includes such things as degree, curvature, and length of slope, and distance to and depth of stream channels. In an area of uniform climate and parent material, relief largely, if not entirely, determines drainage. Thus a *catena* includes soils developed on all kinds of

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relief existing within a region, whether or not associated geographically, as long as they are developed from the same, or nearly the same, kind of parent material.

It is important to note that Milne included within a catena all soils underlain by similar *parent rock*, whereas the United States workers group together only those soils formed from similar *parent material*. Soils at the footslopes on colluvial deposits are placed in a separate catena from those on the upland, according to current American practice. Since Milne did not make this distinction, the term *catena* as he used it was *not* synonymous with *toposequence*.

Milne used the catena as a cartographic unit in reconnaissance surveys, and the members of any catena were determined by geographic association. In detailed survey work in the United States, the catena is seldom, if ever, a cartographic unit, but rather is an inferred grouping to emphasize or clarify genetic relations among soils. The catena, as defined in the United States, is unsuitable as a cartographic unit for two important reasons: First, very rarely will all members of a catena occur in geographic association because of limitations in kinds of relief between any two ridge crests. Second, even in regions of uniform parent rock, interruptions of colluvial and alluvial parent material are common. Two or more members of a catena that occur as a geographic unit are often designated, however, as a *catenary complex* (or *catenary soil association*) and at times may serve as a cartographic unit on soil association maps.

Studies of catenary relations of soils, and the grouping of soils into catenas, are of very wide interest in the United States, particularly among field workers in the humid areas.<sup>2</sup> Such interest is readily understandable. Situations occur repeatedly within small areas, such as a county or a township, where all the factors of genesis except relief are essentially constant. Slope, the major component of relief, usually varies gradually, and it is easy to observe the concurrent variations in soil properties within small areas and relate them to relief. Equally favorable circumstances are encountered much less often for observing the effect that other factors of soil formation have on soil properties. For example, local changes in the factors parent material and time are apt to be abrupt or extreme rather than continuous, and often they are associated with major changes in relief. Inferences about the genetic influence of these other factors are less easily developed. For such reasons, catenary groupings have been most widely used in developing soil keys.

*Grouping soils into catenas.* The catena is usually developed around (and often named for) the zonal soil (if it exists) on any given parent material, which implies that the range in parent material properties within a catena is approxi-

<sup>2</sup> Relatively few field men have published their views and theories on catenas. A partial summary of current field practice and some recommendations as to future practice in regard to catena groupings are given in the unpublished report of the "Committee on Soil Catenas and Soil Families" to the correlation staff of the Division of Soil Survey of the United States Department of Agriculture (Cline, et al., March 1945). In general, the present discussion of catenas is in harmony with the views presented in the committee report.

mately the same as that allowed within a soil series. If the same parent material occurs on steep slopes with excessive runoff, usually a Lithosol, and sometimes an intergrade to it, will be included. If the parent material occurs on gentle to level slopes where drainage is impeded or seepage results, various intrazonal soils also will be included. In a humid region the intrazonal soils may include Planosol, Half-Bog or Wiesenboden, and Bog. In subhumid to arid regions, one (or several) of the halomorphic intrazonals or a soil with properties similar to those of the zonal soil of a more humid area will be included. Soil properties affected by geologic (normal) erosion and hydrology will show a continuous variation throughout the catena if it is "complete" (includes all kinds of relief). Each member series presumably will represent the average or mode for some definite interval of that range of variation in properties.

*Soils grouped with two or more catenas.* Evidence suggests that with increasing restriction of drainage, greater differences in the properties of the parent material are required to produce sufficient change in the soil profile to justify a series separation. Consequently, the same intrazonal soil may be grouped in two or more catenas with zonal soils which are developed on rather similar or related parent material. For example, Dickson is the moderately well drained "Semi-planosol" in both the Cookeville and Baxter catenas. Guthrie, a poorly drained Planosol, is a member of many catenas. Clearly, establishment of a new soil series does not automatically necessitate establishment of additional catenary associates.

*Comparisons among catenas.* If two or more catenas are compared, the relative range in properties of soil series assumed to have analogous positions in the grouping is readily apparent. Comparisons may suggest changes in the limits of variation of certain properties of soils within a catena. In certain cases, the redefinition of limits of variation may go as far as combining some series or subdividing others. It is important, however, that series not be altered or created just to make them fit into a standard catenary framework. There has been a tendency to establish new series by deduction, thus "completing" a catena, rather than to build the catenas from the mapping units. A single series may properly cover a rather wide range of drainage conditions in one situation, and another series, a rather narrow range in a different situation. It should not be assumed that series in different catenas should be separated at the same degree of drainage.

#### *Kinds of profiles within a catena*

Bushnell (5) has suggested that eleven "major profiles" be recognized in upland and terrace catenas and nine in alluvial catenas. Though he does not mention colluvial parent material, presumably young colluvium would be analogous to young alluvium, and old colluvium be handled like terrace and upland. Following is a brief summary of Bushnell's proposal, with the more important of his criteria for defining the major profiles of upland catenas:

MAJOR PROFILE	PERCENT-AGE SLOPE	SUBSOIL COLOR		INFERRED DRAINAGE	NOTES
		Upper	Lower		
I	0-1	Gray	Mottled gray	Poorly drained	Planosol
II	1-2	Mottled	Mottled	Imperfectly drained	Planosol
III	2-4	Yellow	Mottled	Moderately well drained	"Semi-planosol"
IV	4-15	Brown	Brown	Well drained	Zonal
IV C	10-25	Reddish-brown	Reddish-brown	Well drained	Zonal
V	0-25	Reddish-brown	Reddish-brown	Excessive internal	Drouthy
VI	20-55	Variable	Variable	Excessive external	Lithosol
VII-IX	0-1	Gray or mottled	Gray or mottled	Very poorly drained	Half-Bog' (Wiesenboden)
X	0-1			Very poorly drained	Bog

In alluvial (and colluvial) catenas, "major profiles" IVC and VI are omitted (X probably should be) and the slope and color descriptions are different, but the same drainage inferences apply as for upland major profiles. However, *all* alluvial catena members would be azonal (assuming that no Bogs occur).

The major profile criteria were developed to fit conditions in the humid region (Indiana) and it is clear that they would not be applicable in the subhumid and arid regions. In fact there are many situations in the humid region where they require modification, as Bushnell's use of different schemes for upland and bottomland catenas suggests at once.

Bushnell (4) recognizes that certain major profiles can not or may not occur in certain catenas. For example, V profiles are developed only over coarse textured materials; IV profiles are invariably absent in such catenas. On heavy textured and impervious parent material, he suggests that usually IV (and often III) profiles do not occur because internal drainage will be imperfect even on "normal" slopes.

The length of slope and the distance to a stream channel, as well as permeability of parent material, affect the relation between slope gradient and internal drainage. Long uniform slopes often will be imperfectly drained toward the bottom, due to seepage. Level, but narrow, divides may be well drained. Soils that Bushnell would class as III profiles (Dickson, Grenada) have been observed on slopes as steep as 10 per cent, and soils considered zonal (Memphis, Lexington) have been observed on slopes of less than 1 per cent.

Profiles I, II, and III are very rare, if they exist at all, on parent material derived from tilted limestones. Dewey and Decatur soils in the Great Valley of East Tennessee have no imperfectly drained catenary associates, apparently because the bedding planes and underground channels permit adequate percolation even on level areas. Underground rivers in Karst regions often provide

similarly good drainage for level lands. The alluvial and colluvial parent materials in these regions, however, usually give rise to the expected catenary sequence of soils.

The color descriptions given by Bushnell also must be modified somewhat in making inferences about drainage in other parts of the humid region. For example, the color range of profile IV must be broadened to include red in the southern states. The organic matter in the dark-colored Prairie soils masks the mottling to considerable depth. Relic mottlings may persist in soils now well drained because of the progress of dissection.

Generalizations about the properties of soils classified in any "major profile" are rather limited, unless attention is restricted to similar catenas (those which differ but little in parent material, age, vegetation, and climate). Because pan development, degree of leaching, and slope gradient may vary greatly within any column, as compared to variations in drainage conditions as inferred from profile color, most soil keys based on catenary relations emphasize degree of drainage instead of profile properties in the column headings. Bushnell's work has helped standardize drainage inferences and has offered a convenient notation for designating drainage conditions (assuming that "major profiles" VII, VIII, and IX are considered as one drainage group as indicated in the foregoing summary). Karraker and Ligon (9) have followed this notation rather closely, as have many field workers, some of whom have not published their keys. Bushnell (6) has cited many of the papers in which reference is made to catenary relations.

#### *The catena as a natural taxonomic unit*

Bushnell (4) has suggested the use of the catena as a taxonomic unit. This view involves the confusion of soil properties which are observed, and the pedogenic factors which are inferred. He defines a catena as including "all soil series which are homologous in characteristics due to climate, time, vegetation and parent material, but which differ in characteristics due chiefly to varied drainage and land form." This definition implies that each factor of genesis produces a certain set of soil properties independently of other factors, which seldom is true. A soil property is the result of the *interaction of all* factors, and will vary to some extent if any factor changes. Thus, members of a catena may not be *homologous* for any soil property, but they will exhibit a continuous range in properties if the relief varies in a continuous manner. Actually, Bushnell (4) clearly recognized this fact when he said that soils and soil properties "naturally form a continuous spectrum. . . ." It is proper to conclude, as already emphasized by Brown and Thorp (3), Jenny (8), and others, that the catena as used by Bushnell and other United States workers is a genetic grouping inferred from field observations.

Greene (7) considers the catena as defined by Milne to possess attributes of a taxonomic *unit*. He points out that material is translocated not only vertically, but also laterally. For example, some of the soluble salts of the Solonchak have been derived by seepage from an adjacent zonal soil. Such a concept, though deserving of consideration and study, is beyond the scope of this paper.



## GENETIC GROUPING ACCORDING TO TIME: THE CHRONOSEQUENCE

A group of soils the differences in properties of which can be attributed to differences in time during which the pedogenic forces have been operating would constitute a chronosequence. This statement implies that the other factors of soil formation have been uniform, or essentially so, for all members of any chronosequence. Any material change in one or more of the other factors would give rise to members of another chronosequence. The contrast in properties between soils of the bottomlands and uplands is clearly evident in nearly every area. These soils usually do not belong to the same chronosequence, however, because differences in relief and parent material occur also.

Jenny (8) has cited Shaw's (13) "soil families" as examples of chronosequences. Bray (2) and Smith (14) have interpreted the variation in properties of soils occurring on loess in Illinois as due to "effective age." In the area they studied, loess varies continuously in depth from several hundred inches to less than 40 inches. The rate of leaching and weathering during loess deposition varied inversely as the depth of loess. Soils occurring across the area on comparable relief show a concurrent gradation in acidity, intensity of eluviation and illuviation, and other properties which can be interpreted in terms of degree of profile development, or "maturity." Bray (1) suggested the term *maturity series* to designate such a group of soils exhibiting different degrees of profile development. There is some reason to interpret the grouping as a lithosequence, but Smith (14) presented convincing arguments for Bray's suggestion. Five different catenas of soils developed under grass were recognized in field surveys. Thus, each chronosequence (one for soils of each kind of relief) consists of five soils.

Within a limited area, such as a county, not more than one or two members of a chronosequence usually occur; over larger areas, as a state, discovery of additional members is more likely. Obviously, the chronosequence will seldom prove suitable as a cartographic unit, even on small-scale, generalized maps; nor do chronosequences serve well as the major basis of soil keys in many cases. Nevertheless, arrangement of soils into chronosequences may prove helpful in understanding relations between soils. The development of the "maturity" grouping of the Prairie soils by Bray, Smith, and other Illinois workers constitutes a most significant advance in the understanding of the genesis and extreme variations in morphology of this great soil group.

## GENETIC GROUPINGS ACCORDING TO PARENT MATERIAL: THE LITHOSEQUENCE

The term *fasc* (meaning *bundle*) has been suggested by Milne (10) to designate a soil association the members of which differ in properties presumably because of differences in parent material as well as differences in relief. Bushnell (4) has suggested the term *byndel* to designate a group of catenas developed from different parent materials but of similar age. Neither *fasc* nor *byndel* has the same restricted significance as Jenny's term *lithosequence*, which should be defined as a group of soils of similar age and "kind of profile" developed under similar conditions of climate and vegetation.

An example of a lithosequence is afforded by the Prairie soils occurring on

glacial till in northeast Illinois. The clay content of the unleached till, as reported by Wascher and Winters (18), varies in a nearly continuous manner from less than 10 per cent to more than 50 per cent. Field observations indicated a close correlation between till texture and soil properties, a conclusion substantiated by Stauffer (15) in the laboratory. Four soils were recognized, Saybrook, Elliott, Swygert, and Clarence, developed respectively from tills of medium, medium heavy, heavy, and very heavy textures. The field-mapping problems in this area were clarified greatly by the studies leading to development of this lithosequence.

Another example of a lithosequence is to be found in the Great Valley of East Tennessee where the limestones and dolomites vary in their content of clay and chert impurities. Parent materials residual from the weathering of these rocks occur in close association because of faulting and folding with resultant tilting and displacement of the strata. Thus, a recurring pattern of associated parent materials is found across the valley; those high in chert resisted erosion and usually constitute ridges, whereas those low in chert generally occupy valley positions. The Clarksville soils are developed on the most cherty material and Decatur soils on almost chert-free material; along with the soils developed on intermediate parent material, they constitute the Clarksville-Fullerton-Dewey-Decatur lithosequence. Profiles intermediate between the modal conditions for each soil series are common. A knowledge of the lithosequence relation of soils helps in proper grouping of the intermediate profiles.

#### GENETIC GROUPING ACCORDING TO CLIMATE: THE CLIMOSEQUENCE

Much work has been done on climatic classification of soils, but relatively little with grouping soils into climosequences. One reason is that major changes in climate usually involve changes in native vegetation, and therefore differences in soil properties cannot be attributed to climate alone. Another complicating factor is that parent material is seldom uniform over areas large enough to involve several climatic zones. Situations favorable to the study of climatic effects are afforded often by mountain areas where "vertical zonality" of soils exists. Thorp (16) and others have described such situations. But even here changes in vegetation accompany many of the climatic changes.

The tall-grass plant association originally covered parts of two rather distinct climatic zones from Indiana to Nebraska (12). Locations may be found throughout the tall-grass area where relief, parent material, and time are closely alike. The soils representing the range from Prairie to Chernozem on locations of comparable relief, age, and parent material (Marshall-Moody) would constitute a climosequence.

The slow change of climate with distance (except in mountainous areas) makes climate essentially a constant in local areas as in a county (or even in a small state). Thus, in detailed surveys, the men have little opportunity usually to study climatic variables. This may be an important reason why climosequences are not more thoroughly discussed in soil literature.

## GENETIC GROUPING ACCORDING TO VEGETATION: THE BIOSEQUENCE

Several factors complicate the study of biosequences. It has already been mentioned that changes in vegetation usually accompany changes in climate. Also, changes in relief and parent material frequently alter the kind of vegetation on the land. Furthermore, in regions of intensive agriculture, it is difficult to determine what type of native vegetation originally covered any particular land area. It becomes a difficult problem, then, to find soils among which differences in properties are attributable entirely to differences in native vegetation.

One area favorable to the study of biosequences is the eastern part of the Prairie region where forest, tall-grass, and "park" plant associations all occurred before settlement by white man. According to available records, all three types of plant associations were found on level to rolling topography and on a variety of parent materials of different ages. Jenny (8) has cited the Parr-Octagon-Miami soils of Indiana developed on till as an illustration of a biosequence of zonal soils. The Parr is a Prairie, the Miami a Gray-Brown Podzolic, and the Octagon is transitional between them. Another example of a biosequence of zonal soils (developed on loess) is Tama-Downs-Fayette. Biosequences consisting of intrazonal soils have also been recognized.

The members of a biosequence on old parent materials differ much less in properties than do those on moderately young parent material. This fact was implied in discussing the chronosequence of Prairie soils; with increasing age, Prairie soils come to resemble more and more closely the Gray-Brown Podzolic soils. A biosequence of very poorly drained soils (Wiesenboden and Half-Bog) does not exhibit the wide range of properties observable in a biosequence of moderately to well-drained soils. These and other relations emphasized by arranging soils in biosequences indicate the importance of this genetic grouping.

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# INTERPRETIVE SOIL CLASSIFICATION: AGRICULTURAL USE AND MANAGEMENT

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The basic soil classification tells us what the soils are like, and how individual kinds resemble and differ from one another. This basic information permits us to group the soils into classes defined in terms of suitability for particular uses or management practices. Such classes may be defined in terms of predicted suitability for a crop or series of crop rotations, or need for different farming practices, such as tile drainage or contour cultivation.

Such interpretive soil classifications are made possible only as we observe the results of using definite kinds of soils in specific ways, either in experiments or in the year-to-year experience of farmers.

The variety of interpretive soil classifications that can be made for agricultural use and management is very great. The limitations are those of our knowledge of how crops behave and of what practices are of benefit on soils of known characteristics. Within these limitations, the classifications we choose to make are governed by the purposes we foresee for them. Once the basic soil classification is made, any one of many interpretive classifications can be made according to the kind of problem, the evidence to support predictions, and the preference of the classifiers.

## CLASSIFICATIONS ACCORDING TO SUITABLE MAJOR USES

One kind of interpretive soil classification for agriculture is that in which we deduce from the characteristics of the soils, as shown in the basic soil classification, which soils are suited to rotation crops, which only to permanent pasture or forest, which only to forest, and which to none of these uses. This we might regard as a classification of soils according to the major uses to which they appear suited. It is of particular use in areas likely to be opened for settlement, such as Alaska.

It is recognized that the soil evidence used in making such predictions may need to be weighed, in marginal cases, against such considerations as accessibility, or the prospective market for the kind of crop that can be grown.

Following is an example of a simple interpretive classification in terms of suitability to major farm uses, adapted<sup>2</sup> from a more elaborate classification contained in the soil survey report for Hamblen County, Tennessee (1):

1. Soils suited to tilled crops or permanent pasture
  - Abernathy silt loam
  - Decatur silt loam
  - Dewey silt loam

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<sup>2</sup> Many soils are omitted to save space.

- Fullerton silt loam
- Leadvale silt loam
- Clarkville cherty silt loam
- 2. Soils unsuited to tilled crops but suited to pasture or forest
  - Armuchee silty clay loam, eroded phase
  - Dewey silty clay loam, severely eroded hilly phase
  - Tyler silt loam
  - Melvin-Atkins silt loams (undrained)
- 3. Soils unsuited to tilled crops or pasture but suited to forest
  - Litz shaly silt loam, eroded phase
  - Upshur-Litz silt loams
  - Lehew very fine sandy loam
  - Rough stony land
  - Rough gullied land

More elaborate classifications of this general kind with more narrowly defined classes may be designed, depending on the need for them, and the evidence to support them.

#### CLASSIFICATIONS ACCORDING TO SUITABLE CROPS

Similar classifications may be made to group soils according to their suitability to individual crops (6), for example<sup>2</sup>:

- |   |   |
|---|---|
| 1. Excellent soils for sweet potatoes <ul style="list-style-type: none"> <li>Amite sandy loam and fine sandy loam</li> <li>Blakely sandy loam and fine sandy loam</li> <li>Cahaba sandy loam and fine sandy loam</li> <li>Norfolk sandy loam and fine sandy loam</li> </ul> | Durham sandy loam and fine sandy loam   |
| 2. Good soils for sweet potatoes <ul style="list-style-type: none"> <li>Ducker sandy loam</li> <li>Norfolk sandy loam, deep phase</li> <li>Cecil sandy loam and fine sandy loam</li> </ul>  | 3. Fair soils for sweet potatoes <ul style="list-style-type: none"> <li>Appling coarse sandy loam</li> <li>Cecil sandy loam, rolling phase</li> <li>Cecil gravelly sandy loam</li> <li>Cecil coarse sandy loam</li> </ul>     |
|   | 4. Poor soils for sweet potatoes <ul style="list-style-type: none"> <li>Amite clay and clay loam</li> <li>Bibb series</li> <li>Coastal beach</li> <li>Georgetown series</li> <li>Grady series</li> <li>Leon series</li> </ul> |

Each of these classes can be translated into map areas showing their location. Interpretive classifications of this sort can be of special benefit in areas where new crops or those with which farmers have had little experience are under consideration. Ramie, for example, is a relatively new crop along the Gulf Coast. As research and field trials on representative soils disclose the soil characteristics favorable to this crop, an interpretive soil classification can be made to show on maps the soils where ramie production offers promise of success, provided of course, the soils have been mapped according to the basic classification system.

<sup>2</sup> Many soils omitted to save space.



TABLE 1

*Rating of soils of the Salt Lake area, Utah, as to their suitability\* for crop growing*

SOIL	SUITABILITY FOR CROP PRODUCTION
Draper loam Red Rock loam Red Rock clay loam Welby loam Parleys loam Taylorsville loam Taylorsville silty clay loam St. Mary's loam	First-class soils. Very well suited to a variety of crops under irrigation; those of fine texture moderately well adapted to growing wheat under dry farming.
Red Rock silty clay loam, poorly drained phase Draper loam, poorly drained phase Logan loam Decker loam	Potentially First- and Second-class soils. Well suited for crop-growing under irrigation if properly handled. At present excellent to poor, depending on drainage and concentration of salts.
Bingham loam Bingham loam, deep phase Knutsen loam Draper coarse sandy loam Red Rock gravelly loam	Second-class soils. Well suited to crop-growing under irrigation; particularly well adapted to fruit farming; moderately well adapted to growing wheat under dry farming.
Bingham gravelly loam Bingham very gravelly loam Wasatch loam Churchill loam	Third-class soils. Fairly well suited to crop-growing under irrigation, especially fruit farming or dry farming; grazing.
Wasatch coarse sandy loam Knutsen gravelly loam	Fourth-class soils. Fairly well suited to fruit farming if properly handled; poorly suited to other crops grown under irrigation; poorly suited or unsuited to dry farming.
Gooch loam Airport loam Terminal loam Bingham stony loam	Fifth-class soils. Poorly suited or unsuited to irrigation or dry farming; furnish poor to fair pasture.
Saltair clay Rough broken and stony land Riverwash	Sixth-class soils. Unsuited to farming. Most areas have some (generally low) value for grazing.

\* Adapted from a more elaborate table in the Soil Survey Report of the Salt Lake Area, Utah (3). Many soils have been omitted to save space.

## SOIL RATINGS

Closely related to those already described is the interpretive classification known as the *soil rating*. Here numbers are used to indicate the relative position of a soil in an array grading according to quality from excellent to very poor.

TABLE 2

*Average acre yields to be expected over a period of years on some soils of Tama County, Iowa, under different systems of soil management\**

SOIL (TYPE, PHASE, OR LAND TYPE)	SYSTEM OF SOIL MANAGEMENT					ESTIMATED AVERAGE ACRE YIELDS OF					
	Crop Rotation†	Applications of			Engineering aids‡	Corn	Soybeans	Oats	Clover and Timothy	Alfalfa**	Pasture††
		Lime‡	Fer-tilizer‡	Ma-nure‡							
			lb.	tons		bu.	bu.	bu.	tons	tons	cow-acre days
Bremer silt loam	CCO	0	0	0	Tile-drained	55	24	40	‡‡	—	150
	CCOM	0	0	4	Tile-drained	65	26	45	1.4	—	190
	CCOM	Yes	0	8	Tile-drained	75	28	50	2.0	3.8‡‡	—
Bremer silty clay loam	CCO	0	0	0	Tile-drained	40	18	30	‡‡	—	140
	CCOM	0	0	4	Tile-drained	50	20	35	0.8	—	170
	CCOM	Yes	0	8	Tile-drained	60	22	40	1.2	2.0‡‡	—
Buckner sandy loam	CCO	0	0	0	None	10	4	15	0.2	—	20
	CCOM	0	0	4	None	15	8	20	0.4	—	40
	COMM	Yes	200	8	None	30	14	35	0.6	0.8	—
Carrington loam	CCO	0	0	0	None	30	10	27	‡‡	—	100
	CCOM	0	0	4	None	45	14	40	1.2	—	170
	CCOMM	Yes	2000	8	Contour-cultivation	60	22	52	2.0	3.4	—
Carrington loam, eroded gently rolling phase	CCO	0	0	0	None	25	4	17	‡‡	—	70
	CCOM	0	0	4	None	35	8	27	1.0	—	140
	COMM	Yes	200	8	Contour-strip	50	16	40	1.7	3.0	—
Carrington silt loam	CCO	0	0	0	None	35	12	30	‡‡	—	105
	CCOM	0	0	4	None	45	16	40	1.4	—	180
	CCOMM	Yes	200	8	Contour-cultivation	60	24	52	2.0	3.6	—
Carrington silt loam, eroded gently rolling phase	CCO	0	0	0	None	25	6	20	‡‡	—	80
	CCOM	0	0	4	None	35	10	30	1.2	—	150
	COMM	Yes	200	8	Contour-strip	55	18	45	1.8	3.2	—
Carrington silt loam, eroded rolling phase	CCO	0	0	0	None	20	2	15	‡‡	—	60
	CCOM	0	0	4	None	30	6	25	0.8	—	110
	COMM	Yes	200	8	Contour-strip	50	12	40	1.6‡‡	2.8	—

Soil ratings may be made for individual crops, crop varieties, classes of crops, rotations, or for agriculture in general (4, 8). They may be based directly on the evidence of yield experience, or they may be derived from a consideration of soil characteristics that are believed to affect production and quality of crops.

Where evidence is inadequate to support yield predictions, relative ratings based on judgments formed from a study of soil characteristics and plant requirements afford a means of recognizing degrees of difference in the desirability of soils for particular purposes. Table 1 illustrates a rating of soils according to their suitability to farm crops.

#### CLASSIFICATIONS ACCORDING TO PREDICTED YIELD

A form of interpretive classification that distinguishes soils according to their productivity for individual crops is that in terms of expectable or predicted yields of each crop under specified management. This requires some evidence of yields from farm experience on the individual soils to be so classified. Tables may be developed to show the yield predictions for each class of management on each soil as illustrated by table 2.

The soils of this table are arranged alphabetically for ease of reference, and hence do not afford an arrayed classification, but they may be readily regrouped into arrayed classifications according to yield class intervals for individual crops

\* From unpublished manuscript of the Soil Survey Report for Tama County, Iowa, by A. R. Aandahl, and others. Data for many of the soils are omitted to save space.

† The crops included in the rotations are indicated by the following letters: C, O, and M. C means corn with one exception: when average acre-yield of soybeans is estimated, one crop of soybeans is substituted for one crop of corn in the rotation, except for continuous corn, when it is considered that soybeans are raised every third year. O indicates oats. Meadow, M, is meant to include a mixture of timothy with red, white, and/or alsike clover except when the yield of alfalfa is estimated or when there are 3 or more years of meadow in the rotation. Meadow is meant to be alfalfa for these two exceptions.

‡ When lime is included in the system of soil management, it means one application during the rotation in amounts sufficient to neutralize the soil acidity. It is applied prior to the planting of the legumes.

§ Fertilizer application is superphosphate (20 per cent  $P_2O_5$ ) on oats.

¶ Manure applications are made once during rotation on first or second corn crop.

|| Grassed waterways are included with contour cultivation and contour strip cropping.

\*\* Because alfalfa is very sensitive to acid conditions, no estimate of yield is given except under the system which includes lime.

†† Only two systems of management are defined for purposes of estimating productivity of the soils for pasture. System A (first line) is as follows: 1. No application of lime or fertilizer is made; 2. the vegetation consists principally of grasses, although no effort is made to improve the species or to add legumes; 3. weeds are not eradicated; 4. the pastures are not overgrazed. System B (second line) is as follows: 1. Enough lime is applied every 6 to 10 years to maintain neutrality of the soil; 2. a good stand of grasses and legumes is maintained; 3. phosphate fertilizer (125 pounds 20 per cent  $P_2O_5$ ) is applied at the time of seeding the legumes and every 6 years thereafter; 4. weeds are eradicated; 5. the pastures are not overgrazed.

‡‡ As defined, the system of soil management does not include this crop in the rotation.

§§ The rotation is COMMM for estimating the average acre-yield of alfalfa.

¶¶ The rotation is COMM for estimating the average acre-yield of clover and timothy.

or rotations or according to relative desirability for rotated crops and pasture, using the yield predictions as evidence.<sup>4</sup>

Where reasonably good evidence for yield predictions is obtainable, productivity classes in terms of predicted yield have the advantage of being less abstract than those distinguished by purely relative descriptive terms, and also lend themselves to the estimation in quantitative terms of production from a farm or field under specified management. Some crops like tobacco and sweet potatoes differ in quality when grown on different soils. Ratings of soils according to quality of crop may be employed to indicate such differences.

#### CLASSIFICATIONS ACCORDING TO SUITABLE MANAGEMENT PRACTICES

Management practices include rotation, fertilization, drainage, irrigation, and so on. Interpretive classifications can be made to show the suitability of soils for practices in any of these categories provided research or experience on the different soils has supplied the necessary evidence.

#### *Tillage*

Methods of tillage differ greatly in different sections of the country, but in each section, the best methods are those that operate in harmony with the character of the soil.

Depending upon the kind of farm machinery available, and the results obtained by its use on soils of known characteristics, we may make interpretive classification of soils with respect to tillage. In the spring wheat belt, and to some extent in the winter wheat belt, extensive areas of heavy-textured soils (clays and silty clays) are plowed in the fall, preferably when the moisture content is about 50 per cent of field capacity. The freezing and thawing crumbles the large clods and aggregates, resulting in a friable coarse granular or fine blocky tilth that requires comparatively little further cultivation for seedbed preparation. The success of this practice is closely associated with soil structure. The practice is not so successful on clay or silty clay of massive structure and is not recommended for many of the associated lighter-textured soils. The following soils are among those which, because of their characteristics, may be placed in an interpretive class for which fall plowing is generally desirable:

Fargo clay and Fargo silty clay—Red River Valley of North Dakota and Minnesota  
Webster silty clay—Story County, Iowa  
Wabash silty clay—Story County, Iowa  
Farland silty clay loam—Billings County, North Dakota.  
Grail silty clay loam—Billings County, North Dakota  
Paul silty clay—Bonneville and Bingham Counties, Idaho

A great variety of interpretive classifications may be used to show tillage practices suited to particular kinds of soils.

#### *Rotation, fertilization, liming, and erosion control measures*

Rotations, fertilization, liming, control of diseases and pests, and erosion control measures are so closely related that recommendations relating to any

<sup>4</sup> Other examples of soils classified according to predicted yields are found in references (5) and (7).

one are made after giving due consideration to the others. Particular practices are recommended after experiments or farm experience on specific soils has shown those to be preferred. Once this is known, interpretive classifications can be prepared. An example is shown by table 2. The rotation of corn,

TABLE 3  
*Suitable management practices for some soils of Jackson County, North Carolina\**

SOILS	ROTATIONS	NI- TRO- GEN	PHOS- PHO- RUS	POTASH	LIME	MANURE	WATER CONTROL	REMARKS
		lbs.	lbs.	lbs.	tons			
Group 1: Congaree silt loam Congaree fine sandy loam Altavista silt loam	1. Corn, crimson clover, 1 year. 2. Corn, small grain, lespedeza 2 years (espe- cially with eilage corn, 3 years). 3. Truck (beans, cabbage), small grain, lespedeza and grass hay, 3 years. 4. Truck (pota- toes) small grain lespedeza, 3 years.	15-20 30-50 40-60 40-60	25-40 70-100 70-120 70-120	15-30 50-70 50-80 50-80	1 every 4-6 years or as soil test indicates  1/2 every 4-6 years or as soil test indicates	None		Nitrogen on corn and small grain at plantings or as top dressing or both. Phos- phate and potash on corn or small grain. Most of fertilizer on truck crops where they appear in rotation.
Group 2: State loam State loam, eloping phase Tusquitee loam Tusquitee loam, eroded phase Tusquitee loam, gently sloping phase Hilwasee clay loam	1. Corn, small grain, lespedeza, 3 years. 2. Corn, small grain, clover and grass hay, 4 years 3. Corn, crimson clover, 1 year. 4. Alfalfa, 4 years; corn, small grain, lespedeza, alfalfa 6-7 years. 5. Truck (beans, potatoes, cab- bage) small grain, clover or lespedeza 3-4 years.	20-40 20-40 15-20 30-50 40-60	70-120 70-120 25-40 200-300 70-120	30-50 30-50 15-30 180-250 40-60	1 every 4-6 years or as soil test indicates  2 or as soil test indi- cates  1 on cabbage and beans, 1/2 on potato land	To corn and alfalfa	Contour Tillage	Potatoes and alfalfa prob- ably should not be grown in same rota- tion (potato diseases). Use boron on alfalfa

\* From unpublished manuscript of Soil Survey Report of Jackson County, North Carolina. Many soils omitted to save space.

soybeans, oats, and meadow, the last rotation listed for Bremer silt loam, gave highest yields when lime was used and 8 tons of manure applied. Table 3 also illustrates an interpretive classification in which soils are grouped and recommendations are made as to management practices.

#### *Irrigation and drainage*

Interpretive classifications may be made to show suitability of soils to irrigation or drainage or to show on which soils specific irrigation and drainage practices are preferable.

The suitability of soils for irrigation depends principally on the potential productivity of the soils under feasible systems of management. Availability of water supply may be taken into account in interpretive soil classifications for irrigation, or the soil classification may be made independently of the factor of water supply.

Following is an interpretive classification in terms of relative suitability for irrigation:<sup>5</sup>

- |  |   |
|--|---|
| I. Soils moderately well suited to irrigation          | Superstition sand, hummocky phase                   |
| Mohave loamy sand                                      | Cajon sand, hummocky phase                          |
| Mohave loamy coarse sand                               | Cajon fine gravelly sand                            |
| Anthony fine sand                                      | IV. Soils unsuited to irrigation                    |
| Anthony loamy sand                                     | Whitlock loamy sand, eroded phase                   |
| Whitlock loamy sand, shallow over Mohave soil material | Whitlock sand, dune phase                           |
| Whitlock loamy sand                                    | Whitlock gravelly sandy loam                        |
| II. Soils rather poorly suited to irrigation           | Whitlock gravelly sandy loam, dune phase            |
| Superstition loamy sand                                | Mohave gravelly sandy loam                          |
| Cajon loamy sand                                       | Dune sand   |
| Superstition sand                                      | Dune sand, low-dune phase                           |
| Whitlock loamy sand                                    | Rough broken and stony land, Whitlock soil material |
| Cajon loamy coarse sand                                | Rough stony land                                    |
| III. Soils very poorly suited to irrigation            | Riverwash   |
| Whitlock sand  |   |

Other interpretive soil classifications can be made to show need or desirability of drainage, danger of salt accumulation, and methods of salinity control and reclamation of alkali-affected soils.

#### CLASSIFICATION OF SOIL ASSOCIATION AREAS

Research and experience on individual soils enable us to make interpretive soil classifications which predict the suitability of soils for individual crops or practices. The experience of whole farms of different sizes and types on different patterns of associated soils permits interpretive classifications of the areas occupied by these associated soils.

The organization and business of representative farms is frequently analyzed by research workers in farm management with the thought of bringing to light those factors in the farm business that appear to have resulted in larger returns. Such farms are usually selected to represent a larger group of farms having somewhat similar characteristics, so that what is learned from the analyses on a few farms may have application to many. One of the characteristics which causes farms to differ from one another is the pattern of soils. Once the soils have been classified and mapped, it is possible to delimit and classify areas having similar soils in association and in this way ascertain the areas within

<sup>5</sup> From Soil Survey, Yuma Desert Area, Arizona (2).

which most of the farms have somewhat similar patterns of soils. After this has been done, it is possible to say that in one of these areas farms that are equivalent in their other characteristics will have somewhat similar opportunities *so far as soils are concerned*.

An interpretive classification of these areas having similar soils patterns can be made in terms of opportunities for farms of specified organization and size. For example, an area containing 20 per cent of soils well suited to intensive crops associated with 80 per cent of soils well suited to grazing, will afford opportunities for very different types and sizes of farms from those on an area where 20 per cent of soils well suited to intensive crops is associated with 80 per cent of soils suited only to forest.

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# INTERPRETIVE SOIL CLASSIFICATION: TIMBER, RANGE, AND WATERSHEDS

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The principles underlying interpretive soil classifications of use in crop and pasture management also apply to interpretive classifications of use in timber, range, and watershed management. Several examples of interpretive classifications are cited in the following pages, but in general, evidence to support such classifications in "wildland" areas is much less abundant than in cultivated areas.

## TIMBER ASPECTS

Extensive areas of soils once occupied by forests have been classified by soil surveys in the eastern part of the United States; in the West, much less has been done along this line. The lower categories of soil classification, particularly the soil phase, applied to these areas have been directed more toward interpretation for production and management of farm crops than for production and management of forest crops. One of the main reasons for this is that extensive areas of these once-forested soils are used and will continue to be used for production of farm crops and for pastures.

The presently forested areas in the United States consist largely of land not suited for cultivated crops. Over large areas, particularly in the western part, there is little basic information concerning the character and geographic distribution of soils—even according to the higher categories of soil classification. It is in these areas, and in cropped areas better suited for forestry, that the need for soil classification and interpretation will increase as the need for timberland management and sustained timber production increases. The higher categories of soil classification are as applicable to forested soils as to any others—indeed, some of the most distinct great soil groups comprise forested soils. The lower categories are equally applicable, provided subdivisions are directed toward useful interpretation for management and production of timber. It is with the lower categories, mainly the soil series, type, and phase, that knowledge of soil-forest relations are needed. Kittredge (9) pointed out the advantages that natural forest areas offer to the study of soils, long undisturbed, in relation to forest type—advantages that cultivated soil areas cannot offer.

Soils are an integral part of forest ecology, and natural differences in forest character often are associated with natural differences in soil character. Herein lies one of the important contributions soil classification makes to forestry—the extension of correlated observations made in natural areas of soils and trees to areas that man may wish to manage for forestry. Veatch (15) has made ex-

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tensive use of soil-forest relations in approximating areas and kinds of original forest cover in Michigan, and Roe (12) has grouped soil types of the originally forested part of the lake states as to their potential cover of pine, pine and oak, oak, northern hardwoods, white spruce-balsam, bottomland hardwoods, coniferous swamp, or nonforested swamp. Shantz (14) has related the principal types of vegetation in the United States to certain soil properties and to dominant soil series and has shown the importance of plants as indicators of soil properties. Recently, in the soil survey of a sample area of the Pringle Falls Experimental Forest in central Oregon, Leighty<sup>2</sup> found that for this locality soil types with characteristics indicating imperfect subsoil or substratum drainage support a nearly pure stand of lodgepole pine, whereas soil types without indications of imperfect drainage support ponderosa pine, either in pure stands or with some mixture of lodgepole pine. Harradine<sup>3</sup> reported that in northwestern Colusa County, California, the forested area boundary has been pushed upward in places as much as 1,000 feet in elevation as indicated by the area of Hugo soils. These and other similar studies have demonstrated that soil types, properly interpreted, can be used with considerable assurance as indicators of past forest cover.

Each soil type, however, is not necessarily distinct as to forest cover, as brought out in several studies, such as the one by Hicock *et al.* (8), who believe such lack of correlation may be due to biological equivalence of two or more soil types or to general excellence of climatic factors compensating for certain soil differences.

Probably the most important interpretation of soils in connection with forestry, as with cultivated crops, deals with productivity. Soil is one of the chief factors governing forest-site quality, and increasing attention is being given this factor in site-quality studies. Roe (12), in addition to classifying soil types of the originally forested part of the lake states as to their potential forest cover, has grouped the soils as to poor, medium, or good sites for aspen, jack pine, hardwoods (sugar maple), oak, and white pine. An example of his interpretive grouping for white pine follows:

POOR SITES	MEDIUM SITES	GOOD SITES
Antigo sandy loam	Antigo loam	Kennan fine sandy loam
Antigo silt loam	Boone fine sandy loam	Kennan silt loam
Plainfield sand	Coloma fine sand	
Vilas sand	Dunning sand	
	Miami fine sandy loam	
	Vilas gravelly sandy loam	
	Vilas sandy loam	
	Zimmerman fine sand	

In east Texas, Chandler *et al.* (4) found that soil type, of all the factors studied, proved the best indicator of site quality for loblolly and shortleaf pine. The relations between

<sup>2</sup> LEIGHTY, W. J. Classification of sites for reforestation. Division of Soil Survey, U. S. Bureau of Plant Industry, Soils, and Agricultural Engineering, Berkeley, California. Unpublished report and survey prepared for North Pacific region, U. S. Forest Service. 1947.

<sup>3</sup> HARRADINE, F. F. Soil survey of the Mendocino National Forest lands in northwestern

mean site indexes and several soil types given in this study and listed here are an example of basic information for interpretive classification:

SOIL TYPE	MEAN SITE INDEX*	
	Loblolly pine	Shortleaf pine
Ochlockonee fine sandy loam.....	103	100
Lufkin fine sand.....	82	74
Segno fine sandy loam.....	81	72
Ruston fine sandy loam.....	80	74
Caddo fine sandy loam.....	78	73
Susquehanna fine sandy loam.....	73	68
Segno fine sand.....	58	62

\* Estimated mean height, in feet, of trees at 50 years of age.

The relation of site index for loblolly pine to soil type and degree of erosion determined by Cooper (6) in South Carolina indicates the possibility of determining site index for second-growth timber in the southeast from consideration of soil type and degree of erosion. Hill and Arnst<sup>4</sup> in Lewis County, Washington, determined site indexes for Douglas fir on specific groups of soils. Considerable differences in site index were found between the soil groups and between north and south exposures within upland soil groups. Other examples of interpretive groupings are given by Coile (5), who also gives an example of a site index map as interpreted from a soil map.

Soil classes and mapping units must be set up with the widest possible uses of the classification in mind, so far as knowledge permits, in order to provide a single basic inventory of soil resources and to permit interpretive classifications of value in several kinds of land management. Where rapid inspection clearly shows an area to be unsuited to farm crops, however, as in some of our steep mountain areas, classification and mapping units may often be more generalized than in cultivated areas. The more important relatively permanent criteria of use in the natural classification of forest soils listed by Lutz and Chandler (10) are also of importance in crop production.

The system of soil classification that expresses soil characteristics affecting the growth of most plants lends itself best to interpretation in the variety of ways useful in forest management. Additional studies of soil-forest relations are, of course, needed for other interpretive classifications of value to forestry.

#### RANGE ASPECTS

Sustained yields of good forage is a primary objective of range management. One tool of good management is a knowledge of the ecological relationships of range plants, since the interaction of all environmental factors is reflected in the

Colusa County, California. Division of Soils, University of California, Berkeley, California. Unpublished report and survey prepared for California Region, U. S. Forest Service. 1946. This survey is part of the cooperative basic soil survey of Colusa County, California.

<sup>4</sup> HILL, W. W., AND ARNST, A. The correlation between land conditions and timber site quality in Lewis County, Washington. Pacific Coast Region, U. S. Soil Conservation Service, Portland, Oregon. 1945. Mimeographed preliminary draft; manuscript awaiting publication in *Journal of Forestry*.

response of native vegetation. Climate, of course, is a primary factor in determining type of vegetation, but within a climatic zone soils exert the strongest influence on range plants. Observations indicate that in natural areas the relation of plant type characteristics to soil characteristics is closer than the relation of most crops to characteristics of cultivated soils. Shantz (14) has related some of the principal vegetation types of the range area to certain general soil properties and to a few representative soil series, but in general there is less specific information on soil-plant relations for the western range area than for any other equivalent area in the United States.

In most places rangeland is of considerably lower value than cropland, and ranch or other management units may cover many thousands of acres. To date relatively little of the range has been classified as to soil, but the need for such classification apparently is increasing as the need for more intensive range management increases. Such detailed information as is obtained by soil surveys of high-value cropland is not warranted for most rangeland, yet soil mapping and classification units must be designed to show soil features in enough detail to meet range management needs. The soil series as defined at the present time appears to be the most generally suitable unit for soil classification and mapping of rangeland other than experimental areas. There is some question, however, whether the range of characteristics allowable in a single soil series in distinctly nonarable rangeland should not be somewhat broader than for a soil series in arable land. In some places, textural class groups, slope, stoniness, and other separations within a series may be necessary, but use of the soil type and soil phase as mapping units normally involves a degree of refinement rarely justified by rangeland value or the practical application of the data. Detailed classification of soils is desirable for experimental range areas and in some places where rangeland is closely associated with arable or potentially arable land being surveyed in detail.

Although studies of soil-range relations have hardly more than started, it appears from the few observational studies so far made that interpretive soil classifications have a definite place in range management studies. Such classifications may indicate

1. Suitability of a soil for producing different types of forage. This is of particular value where it might be desirable to convert the present cover to another forage type, as from sage to weeds or to grass. Bunchgrass may be the climax type for a broad zone, but soil differences within parts of the zone may make conversion to this vegetation type in a specific area impossible or impractical.

2. Yield potentials or the increase in carrying capacity to be expected by improving management practices on poor or depleted ranges. Management practices directed toward recovery of ranges or of those distinctly on a downward trend often have been based on data obtained from surveys of forage alone. Because fundamental soil differences were not considered, adjustments in livestock numbers sometimes have not been great enough to stop physical deterioration of a site or have been too great in relation to potential forage production of a site.

3. Areas where range reseeding might be a desirable management practice to speed recovery on depleted ranges. Reseeding is expensive and for many other reasons it can be done on only a very small part of the total range area. Consequently, proper interpretations of soils in selecting reseeding sites can play an important part in obtaining a higher degree of reseeding success.

4. Areas where fencing and water developments might be more effectively located in accordance with soil differences that affect forage growth. Other interpretive classifications and increasingly precise ones, will undoubtedly develop as soil-range relation studies develop.

The nutritive value of pasture forage as related to soils has received considerable study (1, 11), but in the main the nutritive value of range<sup>5</sup> forage as related to soils is an almost untouched field (3). Nevertheless, certain interpretive groupings appear possible from the work done so far. Studies by Fudge and Fraps (7) in Texas indicate certain relations of chemical composition of immature range forage to chemical composition of soil types. The occurrence of selenium in certain soils of the range country has received exhaustive study by Byers and others, as reported in a series of bulletins beginning in 1935 (2). The nutritive value of range plants will receive more attention in the future, and it is most probable that certain differences in nutritive value will be found to correlate closely with soil differences and with natural areas of soil.

A few studies are under way designed to make site evaluations of rangelands more precise and meaningful by considering both condition of forage type and soil characteristics in a range resource inventory. As one step, this involves classification of soils according to their natural characteristics, followed by an interpretive classification according to management needs.

#### WATERSHED ASPECTS

In some places land is not suited for range grazing or for timber production and yet may have relatively high value for water catchment. The densely brush-covered steep mountain slopes of southern California, particularly in the vicinity of Los Angeles, are outstanding examples of such land. Here erosion control and general water conservation are of such importance and the fire hazard is so great that fire protection is even more intense than for areas of valuable stands of timber.

Determination of the different kinds of soil and their character, particularly as related to character of underlying rock, has been recognized as an essential step in watershed management studies (13), but relatively little has been done in the actual classification and interpretation of soils as a part of hydrologic analyses. Some exploratory work has been done, and recently Colman<sup>6</sup> listed the kind of information desired for each soil of a watershed for hydrologic analysis in southern California:

1. Maximum rate at which the soil will accept water (maximum infiltration rate).
2. Amount of water retained by the soil mantle during periods of maximum and minimum storage.

<sup>5</sup> The distinction between "pasturo" and "range" is a general one only; it is clearly discussed by Cardon *et al.* (3).

<sup>6</sup> COLMAN, E. A. Soil surveying on wild lands: the problem and one solution. California Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California. 1947. Manuscript awaiting publication in the Journal of Forestry.

3. Water-storage characteristics of the underlying geologic formation.
4. Erodibility of the soil.

Colman found that a very intensive and detailed survey of a 900-acre experimental watershed failed to show areas of distinctly different soils. After experience surveying broad areas of southern California national forests in reconnaissance manner, where distinct soil areas and geological formations were encountered and easily distinguished, he concluded that the soil of the experimental watershed consists essentially of only one kind of soil, and that soil differences here are for the most part only random differences within a naturally distinct soil area. In his reconnaissance survey of the Angeles National Forest<sup>6</sup>, eleven natural soil groups are recognized. Each is characterized as to those properties of direct importance in a hydrologic analysis and as to color, texture, relative soil age, and kind of underlying geologic formation. The more extensive survey proved fully as useful when properly interpreted as the very intensive and detailed survey of the experimental watershed.

Watkins and Williams<sup>7</sup> have grouped soil types of the northern Great Plains as to estimated infiltration capacity when wet and when dry and for stated periods to provide information for estimating runoff values necessary in planning dam spillways. The infiltration estimates are admittedly rough, but watershed runoff estimates determined from them and from other data are reported to be in good agreement with estimates of runoff determined by other methods.

Erosion control, reduction of sediment in streams, water conservation, and reduction of floods are of primary concern in watershed management. Only a start has been made in developing interpretive soil classifications of direct use in hydrologic and other analyses of watersheds, but the work so far done indicates that these classifications have a distinct place in such analyses.

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## INTERPRETIVE SOIL CLASSIFICATION: ENGINEERING PROPERTIES

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The history of soil as an engineering material may be traced through literary works from ancient to modern times. Even so, it is only within the last 20 years that engineers have come to recognize soils as something more than mixtures of gravel, sand, silt, and clay. Most engineers still think of soils as a single textural material rather than as a natural body which may consist of the entire range of textures.

The reason for this apparent lag in understanding is that the greatest strides in soil classification have also been made during the last 30 years. Progress in classification accelerated when it became generally realized that soils have characteristic vertical profiles and that these should be observed in their natural environment.

The engineer is learning from the soil scientist how to determine soil characteristics by field studies of the soil profile and how to use these characteristics as a means for classifying the soil into types. The soil types in turn serve as a basis for making predictions of engineering significance. Since soil types are identified by a study of soil characteristics, it follows that, once established, the soil classification is a source of information relative to soil characteristics. From a knowledge of characteristics, the engineer is able to estimate soil properties and to determine the suitability of the soil for engineering purposes.

Such knowledge enables the engineer to prepare more accurate plans, to reduce to a minimum the original construction effort, and to simplify maintenance problems on all engineering structures where earth is one of the principal construction materials. Airfields and highways are the two best known examples of such structures.

Highway and airport engineers are especially interested in the engineering significance of soil science. The highway engineer must work with extensive areas consisting of strips usually about 200 feet wide along the highway right-of-way. The airport engineer is concerned with airport sites ranging in size from  $\frac{1}{4}$  section to more than 4 square miles. In both instances the engineer deals with construction involving low investment per unit of area as compared to dam or building construction. For this reason soil engineering techniques adapted to dam and building construction are too slow and expensive for use in highway and airport work.

Furthermore, in addition to information on soil properties, highway, airport, and military engineers must have information concerning the environment of the site in question. Since soil types are the product of environmental forces acting on a parent material, they serve to reflect environmental information

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with respect to climate, natural vegetation, topographic and geographic position, internal and surface drainage.

This reflected information is important, since soil studies for engineering purposes involve more than classification and laboratory testing. When a soil profile has been examined and classified or when a soil sample has been tested to determine some specific property, the resulting information is accurate only for the point at which the examination was made or the sample collected. It is also necessary to make an area study and to indicate on maps areas with soil profile development sufficiently uniform to be included in a single soil type. The soil type then becomes a unit of mapping. Map boundaries outlining these soil types provide area-significance to soil information in a form that can be transmitted.

The amount of profile variation permitted within a single soil type as outlined on a map depends in part on the scale of the map. Soil maps for highway and airport use are usually large scale (often 100 feet = 1 inch), permitting great mapping detail. Trafficability maps of large areas, on the other hand, may be made at scales so small as to require mapping units consisting of soil associations rather than soil types.

Knowledge of physical soil properties may be gained in two ways: First, through a field study of soil characteristics and soil profiles as described above; and second, through a laboratory study of soil material sampled in the field and tested in some field or headquarters laboratory.

These two methods of studying soils are not completely independent of each other. The field study serves the laboratory study by assuring that samples collected are representative of the materials being tested. The laboratory study serves the field study by providing definite quantitative values for soil properties determined in a general way by the latter. The two methods complement each other. A soil classification survey can be quickly completed and then serve as a means for selecting representative samples, thus eliminating the need for continuous sampling. The resulting reduction in sampling also serves to reduce the amount of laboratory testing necessary. Such an economy greatly increases the efficiency and operating range of the soil engineering personnel.

As experience is gained in soil classification, in laboratory testing, and in associating engineering experience with soil type, there is a corresponding development in ability to determine soil properties without the benefit of laboratory testing. This fact results in a gradual reduction in the number of routine tests required and a gradual improvement in the accuracy with which engineering properties may be predicted.

Soil engineering data are usually associated with the design and construction of specific projects. There are other engineering problems not confined to local areas of limited boundaries. For instance, mechanized warfare has demanded of the soils engineer specific information concerning the trafficability of soils. The physical properties of a soil determine its behavior under load, and consequently become of paramount importance in any system of classification. Each unit of trafficability maps is characterized by a similarity of slope, soil

properties, and topographic position. Ease of movement is based on the expectable performance and is usually qualified under adverse weather conditions.

Research in soils engineering is giving more and more emphasis to clay mineralogy and the chemistry of clay. A complete characterization of the clay of a particular soil lends meaning to the interpretation of data from physical tests. For example, a soil with 15 per cent of a montmorillonite type clay may be just as plastic as another soil with 50 per cent kaolinite clay, and both soils may have similar physical properties. The chemistry of clay is equally important. Two soils with the same quantity of the same type of clay may behave quite differently, depending upon the ions that saturate the base exchange of the clay. A sodium-saturated clay exhibits physical properties which are entirely different from those exhibited by the same clay saturated with calcium. The characterization and classification that provide the engineer with a maximum of factual information will be the most useful.

To summarize, the engineer's interest in soil classification stems from the fact that in highway and airport engineering especially, the soil is one of his principal construction materials. He considers not only line, grade, and surfacing, but he must know how to heal construction wounds in the landscape; he must correctly anticipate seasonal changes in ground-water positions; he must be informed as to the location and suitability of soil materials in the neighborhood; and finally he must know the critical soil and foundation properties from a study of soil characteristics and from laboratory tests.

There are three basic steps by which a mature soil engineering organization brings soil information into play in the solution of engineering problems:

1. *The soil survey.* For airports and highways this includes identifying individual soils and determining their boundaries within the project. The soil characteristics observed will provide the design engineer with most of the soil engineering information needed to prepare plans. In addition, the survey experience gives the soil engineer the intimate acquaintance with the site necessary to make him a valuable consultant to each unit of any organization which will later become concerned with the project.

2. *The field check of plans.* After the soil engineering data have been incorporated in designs, the soil engineer should have an opportunity to field-check plans with design and construction engineers. At this stage he interprets soil conditions for other members of the checking party and at the same time makes sure that information contained in his soil survey has been correctly interpreted and properly used in preparing plans.

3. *Construction inspections.* When the project has been placed under construction, the soil engineer may interpret soil and foundation information for both construction engineer and contractor. As earth cuts are opened and embankments constructed, he examines the grade in detail and determines the exact location and quantities of corrective treatment such as drainage and frost-heave excavation. He serves as consultant in matters involving fill, compaction, drainage, erosion control, materials inventory, and peat swamp treatment, and in the use of soil materials such as topsoil, clay, sand, and gravel.



# SOIL CLASSIFICATION AND SOIL MAPS: UNITS OF MAPPING

IVER J. NYGARD AND FRANCIS D. HOLE<sup>1</sup>

## THE FIELD AS A PROVING GROUND FOR SOIL CLASSIFICATION

Preceding papers have presented the criteria on which the definitions of the categorical units are based in a natural and logical system of soil classification. This paper deals with identification, location on the ground, and delineation to scale on maps of these taxonomic units, which are thus given geographic expression. Field identification and study of soils naturally precede classification. But once a classification is agreed upon, the additional field work involved in making a soil map of an area calls for still further examination and analysis of soil characteristics and field conditions. Thus the soil classification is further tested and developed. To classify and map soils well, the scientist devotes much effort and attention to careful spade work and study in the field. Thus, over the years, soil scientists have gathered and recorded a large part of the reliable data for classifying soils and for predicting their potentialities for use and their management requirements.

## DEVELOPMENT OF THE UNITS OF MAPPING IN THE UNITED STATES

Soil survey work on a national basis was started in the United States about 50 years ago mainly to define and map soil units and to obtain information on their relationship to crops (9). The first scientists of the Bureau of Soils classified soils primarily on the basis of texture and parent material in relation to crop production. Neither the modern concept of the soil profile nor the idea of broad soil groups had yet been formed in this country. Mapping was detailed from the start. For a long time the work continued with both a strong agronomic and a strong geologic bias. In the early twenties Marbut (6) clearly pointed out that a sound classification of soils must be based strictly on soil characteristics as they exist in nature, and not indirectly on inferences. He further emphasized the soil profile as the best and most convenient expression of soil characteristics. Marbut's influence was enormous.

## A POINT AS A UNIT OF OBSERVATION AND AN AREA AS A UNIT OF MAPPING

Soils occupy areas, not merely points where they may be examined. Thus a soil has a defined range in profiles. No two soil profiles are exactly alike, even within a given soil area. The differences between them in a distinct soil area, however, are not significant. These differences may or may not be measurable, but they are not mappable even though moisture conditions are uniform from one point of observation to another. Soil characteristics also change slightly with the seasons. Observations and examinations at each point should be made under uniform conditions or referred to standard conditions and expressed in standard terms. Otherwise, two neighboring points within the same soil area may be mistaken for two different mapping units.

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Great care is necessary in selecting points at which to make official standard soil type descriptions and in recording all significant internal and external characteristics of the soil in standard terminology. Much progress has been made during the last few years in standardizing terminology<sup>2</sup> for color, texture, structure, consistence, and drainage of soils. Standard soil color chips with corresponding color names are now arranged in a convenient chart. A pocket notebook for soil profile descriptions, as suggested by Gardner and Retzer (2), has been found of great assistance in making a complete record of soil characteristics at selected points. Obviously, a field scientist can make complete descriptions of the soil profiles at only a few points of observation within areas of any one soil. But these must be sufficient to establish the modal profile and the limits. A written record of observations made at other points may consist of brief descriptions of measurable variations in characteristics.

A scattered and representative sampling is necessary within a particular soil area to identify the soil and help fix its boundaries. The number of points of sampling needed cannot be fixed. In some areas three may suffice, whereas in others many more are necessary. If observations are too far apart, a mappable soil area may be omitted, thus creating a serious error on the map. Where significant variations in the internal characteristics of soils occur within short distances, the soil scientist will make more observations per square mile than elsewhere.

#### RELATIONSHIP BETWEEN CATEGORICAL AND CARTOGRAPHIC UNITS

Categorical units are devices for describing soils in the system of classification, whereas cartographic units are used to indicate the geographical extent of soils. Units of mapping are the closest approximations to taxonomic units that practical considerations allow. A cartographic unit gives both the location and the extent of a taxonomic unit. The area of soil type may be thought of as having a range of contiguous soil profiles within which soil characteristics do not vary beyond the range permitted within a soil type. Such areas do exist, and in them cartographic units match categorical units. Many soil type areas, however, are not so homogeneous as this. A soil type area may include some spots, too small to show on the map, of other soil types, and a peripheral zone having profiles with characteristics transitional to those of adjacent soil type areas.

The integration of categorical and cartographic units is a major problem confronting a field soil scientist in his day-by-day work. For instance, after examining in the field a soil map made by a beginner, an experienced soil scientist remarked, "This man is a soil profile mapper! An experienced scientist does not map soil profiles; he maps landscapes." Actually, each of these statements is incorrect by itself. One cannot map a single soil profile any more than one can map a single tree. But the experienced man meant that the beginner had not yet learned to enlist the aid of external soil characteristics such as relief and other

<sup>2</sup> A limited supply of mimeographed reports on standard terminology for describing soil profiles is available at the Division of Soil Survey, Bureau of Plant Industry, Soils, and Agricultural Engineering at Beltsville, Maryland.

observable features of the landscape to differentiate the recognizable and map-pable soil units and to locate boundaries. A soil scientist needs to recognize land forms quickly and accurately, but he does more than merely map land forms. He synthesizes observations of both soil profiles and land forms while mapping a soil area.

Although rarely exact, in most areas the patterns of soil areas clearly reflect one or two of the factors of soil formation. For example, figure 1 shows the close relation of soil cartographic units to relief and parent material in a dissected landscape of Houston County in the southeastern corner of Minnesota. The influences of the other three factors of soil formation—climate, vegetation, and time—have been relatively uniform over the region represented by this diagram.

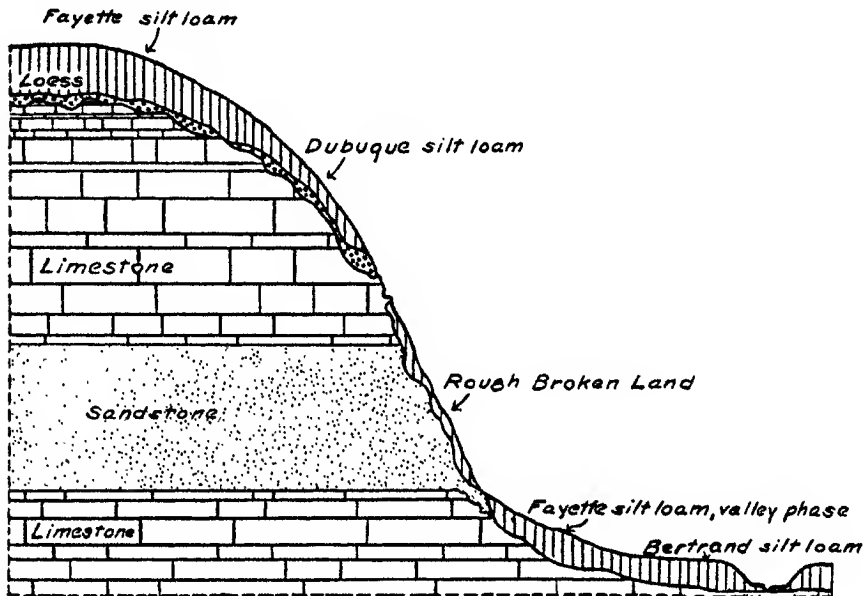


FIG. 1. DIAGRAMMATIC CROSS SECTION OF PART OF A DISSECTED LANDSCAPE IN HOUSTON COUNTY, MINNESOTA

The correlation discovered in the field between soil areas and soil-forming factors, and also between soil areas and land use, confirms the definitions of categorical units.

#### DEFINITION AND USE OF SOIL COMPLEXES, SOIL ASSOCIATIONS, AND LAND TYPES

Unfortunately, the taxonomic units of soil classification cannot always be shown directly on maps. This means, not that the soils in these areas cannot be classified, but rather that the taxonomic units cannot be mapped in detail because of mechanical limitations of map scale or because the smallest practical operating unit of land is far larger than the areas of individual soil types and phases.

Two or more taxonomic units may be so intricately intermingled that they

cannot be shown separately at a practical mapping scale or, if they were separated, the map would be too detailed for use in predicting yields (4). Such intricate mixtures of categorical units are grouped into cartographic units called *soil complexes*. A complex of soil series is designated by the names of two or three of the most important series. In Barron County, Wisconsin, the soils of certain rough morainic areas are mapped as the Milaca-Cloquet-Greenwood Peat complex and as the Milaca-Freer complex. Figures 2 and 3 illustrate the fact that in preparing to reduce field sheets to the scale of publication, very small areas of soil phases and types must be combined into complexes. Complexes may be of phases or types within a series, as well as of phases or types of different series. The proper recognition of complexes in mapping is regarded as one of the greatest single advances in soil surveying (4).

A soil association is a grouping of geographically associated soils which may or may not have similar characteristics (4). The soil complex, already discussed, is one kind of soil association used even in detailed surveys. Relatively large



FIG. 2

FIG. 2. MAP OF 80 ACRES IN BARRON COUNTY, WISCONSIN, SHOWING AREAS OF SOIL TYPES AND SLOPE PHASES



FIG. 3

FIG. 3. MAP OF THE SAME AREA AS THAT IN FIGURE 2, SHOWING AREAS OF SOIL COMPLEXES

numbers of areas of individual soil phases or types that have been mapped in detailed surveys can be grouped into soil associations on maps of reduced scale. The Reconnaissance Soil Map of Langlade County, Wisconsin, shows two soil associations, designated as *Brill-Poskin silt loams* and *Almena-Auburndale silt loams*. The soil types involved could easily be separated in a detailed survey. On generalized soil maps of regions as large as one or more states, soils are grouped into broad associations named after the most extensive soil types included in them (5, 7). This type of map, which is classed under compiled maps, is discussed in a later paper.

In areas where no soil is present, or in nonagricultural areas in which expenditures for detailed surveying are not warranted, miscellaneous land units<sup>2</sup> are mapped (3). Miscellaneous land units are cartographic units which designate land forms or land conditions without classified soils. Figure 1 includes the miscellaneous land unit, rough broken land. Figure 4 represents the miscel-

<sup>2</sup> Formerly called *miscellaneous land types*.



laneous land unit, pitted outwash, as it interrupts level areas of productive agricultural soils in Barron County, Wisconsin. In Michigan, Veatch (8) used the phrase *natural land type* for a cartographic unit by which the mapper subdivides a region into broad areas on the basis of soils, vegetation, and relief.

#### DELINEATION OF UNITS OF MAPPING ON FIELD SHEETS

Recent improvements in techniques of field mapping have facilitated plotting soil boundaries on base maps.

Prior to 1930, fully half the time and effort of a mapper was devoted to constructing a base map upon which to plot the results of his research in the field. The soil scientist located points of observation on the map by laborious, time-consuming pacing and triangulation. In fact, some soil surveyors became more proficient in preparing base maps than in identifying soils and delineating soil areas. The difficulties of plane-table mapping were such that the maps drawn by two or more experienced surveyors of the same section of land, even where soil boundaries were plainly visible on the ground, showed discrepancies.

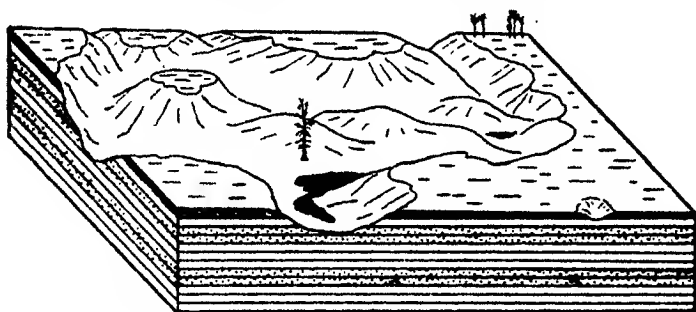


FIG. 4. PITTED OUTWASH, A MISCELLANEOUS LAND UNIT IN BARRON COUNTY, WISCONSIN, INTERRUPTING LEVEL AREAS OF ANTIGO SILT LOAM

After introduction of the aerial photograph as a base upon which to plot soil data (1), the soil surveyor found that he could locate and record cultural, physiographic, and drainage features comparatively easily and far more rapidly than by the plane-table method. Aerial photographs have greatly increased the accuracy of soil maps.

During the last 15 or 20 years, recognition and use of additional mapping units—soil associations and soil complexes—in their proper place have improved soil maps materially. Previously, soil types and soil series had been mapped in complex areas in such a way as to misrepresent the soil pattern by oversimplifying it and, at the same time, by unduly broadening the definitions of soil types and series.

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# SOIL CLASSIFICATION AND SOIL MAPS: ORIGINAL FIELD SURVEYS

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Field soil surveys are intricately linked with soil classification, and development of each is essential to and dependent upon that of the other. The two must evolve together. A natural classification of soils, like that of other groups of natural bodies, must be based directly upon the characteristics of the objects classified. Soils must be studied as entities, and this can be done only in the field where the *whole* soil can be investigated in its natural setting. Field soil surveys offer the most effective method for such studies.

## DEFINITION AND OBJECTIVES

Field soil surveys consist of studying, identifying, and mapping soils in the field; assembling, analyzing, and interpreting facts about the soils and their relationships; and preparing and publishing the results. They show the geographic distribution of soils and are a link between the fundamental and the applied phases of soil science. Soil surveys are too often referred to as soil inventories. Actually, they are much more. Inventories answer the questions: What? and How much? Soil surveys tell not only what soils occur and how much of each, but also where they are and how they are associated. In addition, the survey interprets and evaluates the soils for agriculture, forestry, and other uses.

The broad objectives of soil surveys<sup>2</sup> are as follows:

(a) to classify soils according to their characteristics into units of a uniform system of classification with uniform nomenclature; (b) to show their distribution on maps; and (c) to define their adaptability for crops, grasses, and trees, their management requirements for sustained production, and the expected yields of individual crops under different systems of use and management.

Soil facts established by field surveys provide an accurate basis for accomplishing many specific objectives.<sup>2</sup> Among these are the following:

(a) prompt application of tried and new discoveries in soil and crop management; (b) planning agricultural research and extending its results; (c) determining the potential distribution and adaptability of individual crops and soil management practices; (d) developing rural land classification, rural zoning, and public land management; (e) appraising land for tax assessments, farm loans, and farm purchases; (f) assisting farm buyers, new settlers, and colonizing groups in proper selection of land; (g) planning engineering works as highways and airports, and those for flood control, drainage, irrigation, and

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<sup>2</sup> Kellogg, C. E. Summary statement of research studies and needs. Bureau of Plant Industry, Soils, and Agricultural Engineering, U. S. Department of Agriculture. 1947. [Mimeographed.]

conservation; (h) correlating soil conditions in this country with those of other countries so that applicable experience elsewhere may be available to American farmers, engineers, and agricultural scientists.

Although the fundamental purpose of soil survey work is to serve practical objectives, it must necessarily be based on scientific principles. If such principles are violated, the work loses not only its scientific value but its practical value as well (3).

The field survey itself is a record of facts about the soils, particularly of the more nearly permanent characteristics. Most of the objectives of the soil survey are attained through interpretations of these facts. All types of surveys are not equally adequate for all objectives. The purposes of the survey must be clearly defined before it is initiated.

#### TYPES OF SOIL SURVEYS

Three general types of soil surveys are recognized (3): detailed, reconnaissance, and detailed-reconnaissance. Detailed soil surveys are those in which the soil boundaries are plotted accurately from observations made throughout their courses. Reconnaissance soil surveys are those in which soil boundaries are sketched from observations made at intervals. Detailed-reconnaissance soil surveys are those of which a part of the area surveyed is mapped by detailed methods and the remainder by reconnaissance. These are of two kinds: in one, different legends are used for the two parts of the area; in the other, different degrees of generalization are mapped according to the same legend. Each of the three general types of surveys will vary in degree of generalization according to the character of the landscape, the objectives of the survey, and other factors.

A modern basic detailed soil survey is a comprehensive map and text portrayal of the kinds, amounts, and geographic distribution of the individual soils. As a minimum it must furnish, through development and extension of soil classification, the soils information about the area needed for (a) planning land use and management at the community level, (b) formulating and planning agricultural research and extension programs, and (c) synthesizing, interpreting, and projecting the results of experimentation and experience. Usually the objectives of the survey call for soils information in sufficient detail for planning soil use and management within individual farms and ranches.

Reconnaissance soil surveys are less intensive and narrower in objectives. Generally, the principal mapping units are soil associations or broad soil patterns, rather than individual soils. At a saving of time and expense but at a sacrifice of much information, such surveys are designed to furnish soils information suitable for broad planning and programming at the county, regional, state, and national levels. The degree of generalization will vary among survey projects according to one or more of several factors including the nature of the area and the objectives of the survey. Perhaps the most important need for reconnaissance soil surveys is that of locating areas which merit detailed study in regions where little farm experience is available. Semidesert regions and many parts of Alaska and of the tropics are examples. Such surveys are also useful in obtaining a general knowledge of the soils of regions about which little or no information is available. Such general information is extremely helpful in developing soil classification, and for developing broad regional plans of many kinds. Reconnaissance methods are adapted also to soil surveys of rangelands where extensive use and management of the soils is the general rule and detailed surveys may not be justified.

In reconnaissance soil survey work it is essential that small sample areas be mapped in detail to serve as a guide in making and interpreting the survey.

Reconnaissance soil surveys are of little or no use where good detailed soil surveys are available, because generalized soil maps of all kinds can be lifted or interpreted from detailed soil maps provided these are scientifically sound.

Detailed-reconnaissance surveys are applicable to project areas, large parts of which are suitable for intensive agriculture and large parts of which are not. The latter are mapped in reconnaissance, the former in detail, and the survey of the entire project area is published as a unit.

#### BASE MAPS AND SCALES

The best base map for soil survey work is one that shows accurately the largest number of reference points to guide the placement of soil boundary lines. For most detailed soil surveys aerial photographs of good quality, either contact prints or enlargements, are far superior to other kinds of base maps. The mapping may be done directly on the aerial photographs or on transparent overlays. Good topographic maps are probably the next best choice, and they may be preferable for some surveys such as those of heavily forested mountainous regions. For many areas it is desirable to have access both to aerial photographs and to topographic maps. If no suitable base map is available, the field soil scientist must construct one by plane-table methods (3).

The scale of the base map for detailed surveys is commonly about 4 inches to the mile. This is large enough generally to allow sufficient detail for planning soil use and management on individual farms. Base maps with scales of 6, 8, or 12 inches to the mile are used for special survey projects requiring much detail; and maps of less than 4 inches to the mile are sometimes sufficient for detailed mapping of areas having a coarse soil pattern. Various base maps developed for other purposes are suitable for broad reconnaissance work.

#### KIND AND DEGREE OF DETAIL

It is impossible and even undesirable to show all observable details of the landscape on a soil map. This raises the question: Which soil characteristics and conditions will be emphasized and which will be considered as secondary in the mapping? This important matter must be determined for each project area, and this is not to be done arbitrarily. The degree of detail to be employed and the emphasis to be given to each of the many observed variables must be determined first according to sound principles of soil classification. Also, consideration must be given to the objectives of the particular survey project, general character of the area, kind and scale of base map, ability of the field men, effect on the interpretive value of the soil map and report, and ease with which the map can be read. Even the most competent field soil scientists can be overloaded with essentially useless detail. Boundary lines of little significance should be avoided. They serve no good purpose and have the bad effect of cluttering the soil map and obscuring the significant boundary lines. Minor or transient variations and unusual or freakish conditions are best handled through good field notes and a well-written report.

The widespread notion that a soil surveyor should show all minor details of the landscape on a soil map, just because he is traversing the area at close intervals, is fallacious. Traversing the area is a small part of the total field job of mapping soils in detail. By far the greater part of the field man's effort is directed to soil study, placing the boundary lines accurately on the map, placing and checking other natural and cultural features, observing the natural vegetation of the different soils, studying the geographic relationships among the soils and between the soils and other features of the landscape, and studying the manner in which the different soils are used and managed and how they respond to the several systems and levels of management. Probably one of the worst modern errors associated with soil mapping is that of trying to map irrelevant details of minor or transient landscape features that mean little or nothing to soil character morphologically or agronomically.

Extreme care is needed in designing a survey so as to provide for the kind and degree of detail needed. Skilled soil scientists, who have the objectives of the survey clearly in mind, will emphasize the significant things and ignore or minimize minor details. Much detail is needed in mapping experimental fields and farms because the experiments must be planned and the results interpreted and projected with respect to the soils. The degree of detail required in mapping soils for use in farm planning is somewhat less; and the degree of detail needed for programming diminishes, step by step, from the community level to state,

regional, and national levels. And it is essential that all of this be clearly in mind when the original soil legend of the field survey is prepared, because the legend must conform to the natural system of soil classification, to the scientific method in general, and to the objectives of the particular survey project.

#### PLACEMENT OF SOIL BOUNDARIES ON THE MAP

Even though soil classification and soil mapping are closely linked, they are not one and the same. Soil classification is a science; soil mapping is an art as well as a science. It is impossible to map soils with precise accuracy.

A soil is the product of the interaction of all factors that affect its development, and a variation in any one factor, be it ever so slight, will affect the soil in some way and will influence the effects of the other interacting factors. Each soil is defined to include a reasonable range of many similar profiles, and the range is described with consideration of the total combination of characteristics.

Furthermore, the pattern of soils may be extremely fine textured and complex, and the soil boundaries may be very tortuous, gradational, or both. Thus, a delineated area, even on the most carefully prepared map, will likely include small segments unlike the unit delineated. In some instances two or more soils are too intricately associated to be separated, and the pattern, rather than the individual soils, is mapped, defined, and correlated. If the pattern is uniform as to component soils, the mapping unit is called a *complex*; if it is not uniform in this respect, it is correlated as two or more soils, undifferentiated.

A clear understanding of these limitations of the mapping technique is essential to a like understanding of field soil surveys and of the distinction between taxonomic units and mapping units.

Although soils cannot be mapped with mathematical precision, the aim is to delimit areas predominantly of soils without significant differences, and to separate areas predominantly of soils that are significantly different. Soil boundary lines that do this may be considered to be placed accurately. Placing these boundary lines on the map is by far the most important part of soil surveying. The accuracy with which the soil boundary lines are drawn, more than any other factor, will determine the usefulness of the survey. The ability and professional attitude of the field soil scientists and the character of the soil legend largely determine the degree of accuracy of the placement of soil boundary lines. This relationship between the legend and the quality of mapping must be clearly in mind both in planning and in conducting the survey.

#### THE SOIL SURVEY LEGEND

The mapping legend of a detailed soil survey includes a complete list of soil symbols used on the field sheets and the definitions of all soil units represented by the symbols. Its makeup is extremely important both to the work of making the survey and also to the ultimate usefulness of the survey. The mapping units are defined in terms of soil types, phases, complexes, and miscellaneous land units that are subject to correlation with similar units elsewhere in the standard national system of soil classification and to placement in the higher categories of an international system.

Field soil mapping legends must be kept under strict control if the survey is to be readily correlated and of maximum usefulness to soil classification and to applied soil science. The kind and number of mapping units must be limited to the needs as determined by study before and during the survey. Use of a sound soil legend in field work offers the young soil scientist every incentive to develop in the knowledge and skill of his chosen field. Moreover, the final

published soil map and report, with the mapping units identified by standard nomenclature, described and discussed as individual entities, and carefully catalogued for easy reference, are most useful to soil scientists, agronomists, and the general public.

Great care is needed in formulating the legend to see that proper emphasis is placed where needed to meet scientific standards and the survey objectives. For example, if differences in land use and management are greatly influenced by stoniness, the legend should be detailed as to kinds and degrees of stoniness. In a flat, poorly drained area of potential agricultural value, emphasis in the legend will be needed on texture of solum and substratum and other soil characteristics pertinent to drainage and subsequent use, rather than on stoniness, slope, erosion, or other characteristics that are of little or no relevance in the particular area. In areas where slope and erosion are important it is essential that the slope subdivisions in the legend be adjusted properly to the soils and to the topographic features of the landscape, and that the erosion classes be significant and adequate.

In its simplest form the legend is a list of simple symbols each representing a specific soil mapping unit, such as:

<i>Symbol</i>	<i>Mapping Unit</i>
10	Cecil sandy loam, undulating phase
11	Cecil sandy loam, rolling phase
12	Cecil clay loam, eroded rolling phase

It may be advantageous to use composite symbols for mapping in areas with complex soil patterns involving many mapping units in which one or two variable soil features, such as slope and erosion, require consideration in essentially all units. In such cases, separate component parts of the composite symbols are assigned to these features. For example, if the letters A, B, C, D, E, and F represent increasing degrees of slope and the numerals 1, 2, and 3, increasing degrees of erosion, the legend items listed above would appear as follows:

<i>Symbol</i>	<i>Mapping Unit</i>
10 B1	Cecil sandy loam, undulating phase
10 C1	Cecil sandy loam, rolling phase
11 C2	Cecil clay loam, eroded rolling phase

This mechanical variation in field legends is not essential, but it is sometimes used for simplification and convenience. Its use requires the strictest caution. The soil features of slope and erosion must be considered as integral parts of the soil unit and not as "factors" separate and distinct from the soil. They are not to be appraised or evaluated independently from other soil variables. Indeed, slope, erosion, stoniness, or any other single soil feature has no meaning apart from the other characteristics with which it is associated within a specific soil.

Although composite soil symbols used properly are convenient under certain conditions, they will have bad results in many respects if they are used with the idea that certain soil features or characteristics are to be mapped, defined, and evaluated separately and independent of the soil of which they are parts. Com-

plex symbols used in this way do not constitute a soil legend, and the mapping units would not be definable in terms of whole soils or of taxonomic units of the system of soil classification. This scheme would be without control as to the kind and number of mapping units. Under extreme conditions, the units of mapping might run into thousands for an area of three or four hundred square miles. And a great percentage of these units would be insignificant as to individuality, acreage, or both. Furthermore, satisfactory correlation of the soils would be difficult, if not impossible.

Under such a procedure, the mapping would be unsatisfactory for other reasons also. The field man would have little or no inducement to study the soil as a whole, since he would be attempting to map so-called *soil factors* rather than soils. This would be done, too, on the premise that a certain class of slope or of erosion has a constant degree of relevance to all soils, which is not true. This would be a wide departure from the scientific method. Soils must be studied, identified, mapped, correlated, defined, and discussed—as they are used and managed—as units, and with respect to the *combination* of their many characteristics and features.

If complex symbols are used in the sense that different characteristics of the soil are to be mapped, defined, and evaluated separately, an insurmountable problem is left to the user of the survey map and report. For explanation of each area delineated on the map, the user would have to refer to several parts of the report and read each individual discussion of the different characteristics of the soil in which he is interested. Furthermore, and this would be even more important, nowhere in the report would the reader find the whole soil defined, named, and discussed in its relationship to agriculture. The layman reader would have to interpret for himself the significance of the various combinations of soil characteristics and conditions. This interpretation is one of the most difficult parts of making and publishing soil surveys. The reader is not in position to evaluate and interpret the mapping units. This should be done by the field soil scientist who knows the area, who is familiar with the techniques involved, and who has studied the interrelationships among the many soil characteristics and conditions.

#### AVOIDING SOIL CLASSIFICATION IN FIELD SURVEYS

The basic principle that the *whole* soil must be studied in the conduct of field soil surveys, as an attribute to both the fundamental and the applied phases of soil science, is being violated in several ways.

This is true in field surveys in which schemes are used to classify and map individual soil characteristics or features or interpretations of characteristics with little or no consideration of soils as entities. Whether this is done consciously or otherwise, it is essentially an effort to side-step the job of soil classification at the stage where it is especially needed—in the conduct of the field work of the survey. The procedure is not in accord with the scientific method and, as has been emphasized previously, these surveys will fall short of their expected contributions to the applied phase of soil science.



In the conduct of field soil surveys, some scientists have evidenced a tendency to interpret and apply Marbut's criteria of series (4, 5) too literally and too narrowly. Some field soil surveys are made on the assumption that each soil characteristic listed among Marbut's criteria is to be subdivided arbitrarily into several ranges and that any one soil series may include only one of these ranges. Let us take texture of the solum as an example. It might be assumed that one series would include coarse sands to loamy fine sands; another, sandy loams and silt loams; another, clay loams to silty clays; and a fourth, clays. That is, these ranges in textures would be assigned equal values for all soil series. The field mapping itself would be seriously affected if the survey were to proceed on the assumption that this "rule of thumb" is to be followed.

Misuse of the catena concept (1, 2) is another attempt to avoid soil classification in field soil surveys. Much soil mapping is being done under the assumption, first, that a given degree of soil drainage is invariably associated with certain soil characteristics and, second, that a given range in soil drainage has equal relevance for a great number if not for all soils of the region. And many field men now engaged in soil survey work assume that this range in drainage is sufficient in itself to differentiate soil series.

Soil surveying is a painstaking scientific job. There are no satisfactory streamlined short cuts. Years of careful study have gone into the development of present mapping techniques and a natural system of soil classification. Continued progress will come about through improvement rather than circumvention of the scientific approach in the field study of soils.

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# SOIL CLASSIFICATION AND SOIL MAPS: COMPILED MAPS

A. C. ORVEDAL, MARK BALDWIN, AND A. J. VESSEL<sup>1</sup>

Soil maps, in general, can be classed into two groups: original field survey maps and compiled maps. The fundamental distinction between the two arises from the method of preparation. Field survey maps are made in the field and are based on direct observations of soils. Compiled maps, on the other hand, are made in the office and are based, not upon direct observations in the field, but upon published and unpublished soil data, including field survey maps, and data on related subjects such as geology, topography, geomorphology, vegetation, and climate. Examples of compiled maps are the following: (a) the Soil Map of the United States by Marbut (3) showing the distribution of dominant soil series, (b) the map of Soil Associations of the United States in the 1938 Yearbook of Agriculture (5) showing the distribution of principal associations of dominant soil series, and (c) the map of primary groups of soils in the 1938 Yearbook of Agriculture (2). This paper is concerned with the theory of compiled soil maps.

## OBJECTIVES

A primary requisite in compilation of soil maps is a clear understanding of the objective, which determines the choice of scale and levels of both cartographic and categorical generalization. An objective may be to compile a basic soil map, on a small scale, to show high-level groups of the natural soil classification (1) for study and illustration of relationships of zonal soil profiles to genetic factors, particularly climate and vegetation. Another may be to compile an interpretive soil map, on a small scale, to show the principal areas of soils suitable for food production for high-level analyses and planning in food production. Still another objective could be to compile an interpretive map, on a large scale, to show such things as lime requirements for specified crops.

## GENERALIZED VERSUS SCHEMATIC COMPILED MAPS

The fundamental difference between generalized and schematic maps derives from the difference in methods of compilation. Generalized maps<sup>2</sup> are prepared by eliminating details from soil surveys made in the field, such as the surveys made by the U. S. Department of Agriculture and cooperating agencies. Schematic maps<sup>3</sup> are prepared largely by predicting kinds of soils and their boundaries

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<sup>2</sup> This term frequently is applied inaccurately to compiled maps that simply lack detail regardless of compilation method.

<sup>3</sup> This term sometimes is applied inaccurately to compiled maps that are of small scale, highly diagrammatic, and not necessarily cartographically precise, regardless of method of compilation.

on the basis of established correlations between kinds of soils and sets of genetic factors.

#### COMPILATION PROCEDURES

##### *Generalization*

Generalization is the logical method to use where good soil surveys exist, because such surveys obviously constitute the best information from which to compile other soil maps. The process of generalization is essentially the elimination of detail unimportant to the objective.

Distinction between two kinds of generalization—cartographic and categorical—is important. The first refers to mapping; the second, to classification.

Cartographic generalization means essentially the reduction in number of soil boundaries and is necessary in order to reduce the scale of the map (4). Relatively straight or smooth boundaries are substituted for the original crooked or wavy ones. Small areas of one kind of soil may have to be included in a different but extensive one. New units consisting of associations of map units of the original survey may have to be devised. As generalizations are made at successively higher and higher levels, the map units necessarily become less and less homogeneous, and at very high levels of cartographical generalization, the map units may have so little homogeneity that very few assertions can be made about any particular one. The main problem in cartographical generalization is to eliminate detail in such a way that the maximum degree of homogeneity within map units will be achieved for the particular objective at the given scale.

Categorical generalization means the grouping of soils into successively higher categories (4), as soil types into series, series into families, and families into great soil groups. An important fact about this kind of generalization is that as soils are thus grouped, the assertions that can be made of the groups become fewer. One is able to make fewer assertions about the Barnes family than about the Barnes series, and fewer about the Chernozem great soil group than about the Barnes family.

Confusion between categorical units and map units must be avoided. Categorical units are simply the classes of soils, regardless of how they are shown on maps, or whether they are mapped at all. A map unit may consist entirely of a given categorical unit or of several categorical units in specified or unspecified proportions. Thus, at the level of great soil groups, one map unit might be more than 90 per cent Podzols, another might be about 50 per cent Podzols and 50 per cent Bog soils, and a third might be about 50 per cent Podzols, 25 per cent Bog soils, and 25 per cent Half-Bog soils.

Using detailed soil surveys as the source of information, one can generalize cartographically without generalizing categorically. On a map thus prepared the map units would be defined in terms of associations of soil types and phases—the categorical units of the detailed survey. On the other hand, one also can generalize categorically without generalizing cartographically. On a map showing generalized soil categories, the boundary lines would have the precision of the detailed maps, but the map units would be defined in categorical units of

a level higher than that of soil type, such as series, family, or great soil group. Some boundaries might be eliminated thereby, but not enough to reduce greatly the scale of the map. The reason is that widely contrasting soils occur in small contiguous areas in much of the world. Podzols and Bog soils, for example, form intricate patterns, and categorical generalization even at the highest level would permit elimination of only a few soil boundaries and only a slight reduction, if any, in the scale of the map. Actually, most generalized maps are both categorically and cartographically generalized to some degree.

Use of field survey reports requires correlation and readjustment of the mapping units to those of the map under compilation. If one is compiling maps of several countries, the problem may be particularly difficult because of the differences among the classification schemes used.

Use of field survey reports and maps, which are usually on a large scale, 1:63,360 for example, may also prove cumbersome in the compilation of very small scale maps, such as ones on a scale of 1:20,000,000. This is because of the great volume of material that must be examined for even a little area on the small-scale map. Nevertheless, field survey reports and maps constitute the most reliable information from which to compile other soil maps.

### *Prediction*

Compilation of soil maps for areas for which there are no soil maps and no descriptions of soil morphology must, of necessity, rely on predictions of the kinds of soils and their geographic distribution. Such predictions are based on the assumption that soil is a function of five genetic factors—climate, vegetation, parent material, relief (slope), and age. Maps thus compiled are schematic.

In compiling schematic maps, the scientific method of correlation is employed. This method, as applied to soil genesis, consists of repeated correlations between soil morphology (effect) and sets of genetic factors (cause) in many locations. Following these correlations, conclusions are reached about the sets of genetic factors and kinds of soils that occur together; and predictions thereby become possible. Knowing the sets of genetic factors, one can predict the kinds of soils; and, conversely, knowing the kinds of soils, one can predict the sets of genetic factors. Soil scientists through the years have accumulated considerable knowledge of kinds of soils that occur under many sets of genetic factors. Map compilers use this knowledge to predict kinds of soils where soil data are lacking but information on genetic factors is available.

Limitations exist in predicting kinds of soils. At present, one can rarely predict reasonably well categorical units below the level of great soil groups because this is the lowest level in the natural classification in which the categorical units are correlated with broad differences in climate and vegetation. It is difficult, if not impossible, to predict the particular soil family, series, or type, on the basis of genetic factors alone. Except in very few areas, information on genetic soil factors does not exist in sufficient detail for predictions of low-level units, such as families, series, or types. In many areas, however, one can make reasonable predictions about certain soil characteristics, such as texture and

depth to bedrock, that are differentiating for units below the level of great soil groups; but ordinarily it is not possible to predict all characteristics that are differentiating for taxonomic units below that level.

Moreover, the sets of genetic factors associated with great soil groups in some parts of the world are not known so well as are those of the principal groups in the United States. Such is the condition in the tropics; predictions there are correspondingly more difficult and more likely to be in error.

Another difficulty arises where the combination of genetic factors is considerably different from any under which observations of soils have been made and correlated with sets of genetic factors. Such is true, for example, of the high, arid, and frigid plateaus in Tibet and southern Argentina. Geographic correlations, like those possible for Chernozem soils, cannot be made, and sole reliance must be upon theoretical evaluation of known genetic factors. Under these circumstances the predictions of soils may err considerably.

The concept of soil as a function of the five genetic factors implies that a major change in one factor results in a significant change in the kind of soil. Boundaries between kinds of soil, therefore, may be expected to coincide with one or more boundaries indicating major changes in climate, vegetation, geology, slope, or age—age being inferred chiefly from parent material, physiography, and topography. For certain objectives the effect of man's activities, such as the age-old practice of periodic flooding of rice fields in China, may need to be considered also.

#### COMBINATIONS OF GENERALIZATION AND PREDICTION

In actual practice, one seldom follows exclusively either generalization or prediction procedures for preparing compiled soil maps. Field survey maps seldom cover large continuous areas; hence, one must resort to predictions for intervening areas. On the other hand, predictions based solely upon genetic factors are seldom necessary for extensive areas because at least a few spot observations on soils have been made and recorded for most parts of the world.

The preparation of compiled soil maps for most areas, therefore, entails correlating all soil data available and supplementing these with predictions necessary to give complete coverage. Under any procedure, judgment must be exercised by the compilers, who obviously must be competent soil scientists with an appreciation for geography in general and for soils in particular, and who have knowledge of the relationship of climate, vegetation, geology, and geomorphology to soil genesis and soil morphology.

Predictions without substantiation by reports of all available observations should be used only as a last resort. Predictions always should be supported, or at least not contradicted, by observations of soils or of other features from which inferences about soils can be drawn. A comprehensive search of the literature for fragments of relevant information is necessary. This search requires the study of reports and maps on land use, geology, physiography, topography, geomorphology, climate, vegetation, exploration, and travel.

## MAP SCALE AND CATEGORICAL UNITS

A practical balance must be sought between scale of map and categorical level of classification. On a scale of 1:20,000,000, for example, the categorical level of series would be obviously inappropriate. On the other hand, at a scale of 1:100,000 the level of series might be quite appropriate.

Regardless of the level selected, the geographic occurrence of soils is such that on a small scale nearly all areas of a map unit are more or less heterogeneous. Map unit "A", for example, may be Podzols with inclusions of Bog, Half-Bog, Ground-Water Podzols, and Alluvial soils. Map unit "B" may be an association of Bog and Half-Bog soils with inclusions of Podzols and Ground-Water Podzols. The nomenclature should express the relative heterogeneity of the map units unless such heterogeneity is clearly implied in a covering statement. Misinterpretations resulting from the notion that units on small-scale maps are nearly 100 per cent homogeneous as regards categorical units thereby may be avoided.

Once the categorical level is selected, the definition of map units generally should be brought to that level. Map unit "A" for example, should not be defined simply as "Chernozems" while unit "B" on the same map is defined as "Barnes series." It would be permissible, however, to define map unit "A" as "Chernozems, undifferentiated" and "B" as "Chernozems, Barnes series."

It may be expedient or necessary under certain conditions to show one part of a map at one categorical level and another at a different level. If this is done, the part at one level and the part at another must be indicated clearly. Generally, use of more than one categorical level on the same map should be avoided.

## RELIABILITY

The reliability of compiled maps depends primarily on the reliability of available information. But even where good information exists, great care must be exercised in order to compile maps of maximum reliability. Improper correlation between map units of field survey source and the map under compilation, improper or careless cartographic generalization, or improper or careless categorical generalization, will result in unreliable maps even though the basic data are good.

Where soil maps and descriptions of soil morphology are lacking and the kind of soil is predicted from information about genetic factors, the reliability, admittedly, may not be high. But, on the other hand, the magnitude of error need not be great. For example, one would not predict Tundra soils where the climate is tropical, and neither would one predict lateritic soils where the climate is frigid. One might, however, predict Brown soils where Sierozems exist, and errors of such magnitude might be common. Usually a good approximation, even though in slight error, is considerably better than no approximation at all.

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# SOIL CLASSIFICATION IN THE UNITED STATES

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Direct observation of the soil as the basis on which to determine soil character began essentially in the United States in 1899 with the organization of field parties by the Division of Soils, U. S. Department of Agriculture. It may be doubted whether the early scientists forming these parties realized the revolutionary nature of their work or conceived the significance of future developments.

## EARLY CONCEPTS OF THE SOIL

Previous soil investigators had been, almost without exception, agricultural chemists or geologists. The chemists were dominated by Liebig's mineral theory of plant nutrition—the balance-sheet theory. Soils were sampled and taken to the laboratory for chemical analysis. Except for texture, little, if any, attention was given to morphological features.

It was only natural for the geologists of this early period to conceive of soils as direct products of geological phenomena. For example, Peters (8) classified soils in Kentucky as Silurian, Subcarboniferous, and Carboniferous in accordance with the age of the underlying rock formation. Even though this nomenclature may appear ridiculous today, special credit is due Peters as an early observer of the soil in its natural habitat—the out-of-doors. Other examples of the geological bias in soil classification include *granite soils*, *limestone soils*, *shale soils*, *residual soils*, and *transported soils*.

Farmers used such terms as *post-oak land*, *pine land*, *hammock land*, *corn ground*, *cotton ground*, and *rich loam*.

Hilgard was outstanding among the very few American scientists who recognized observable soil features as distinct from geological phenomena. A recognized geologist and chemist, he was also a soil scientist and soil geographer as early as 1860. In discussing soil analyses at that time, he wrote (3):

“It is often by no means easy to take correctly specimens of soil intended to represent a district of some extent; it is necessary, in the first instance, to study closely all the general characters, and upon that study, to base the selection of representative specimens. And I am convinced that by conscientious observance of this method it is practicable in this State at least, to study the essential features of all the soils entitled to such consideration by the extent of their occurrence, from a limited number of specimens; and without an approach to anything as extravagant as the analysis of ‘the soil of every field’ as has been thought necessary.”

Shaler (9) of the U. S. Geological Survey conceived the soil to be an independent natural body formed through interaction of parent geological materials, weathering processes, plants, animals, and dissection of the landscape. He lamented the lack of a coordinated study that would relate the facts of geology, chemistry, and botany in the formation of soil.

## CONCEPTS OF THE SOIL IN THE NATIONAL SOIL SURVEY

Since initiation of the National Soil Survey, fundamental changes in the very concept of soil have had profound influences on soil classification.

*The soil as a geological body—1899-1912.* With the beginning of field surveys in the Division of Soils in 1899, more intensive and widespread observations were made of the soil in place than had ever been done before in this country. Despite this new departure in soil studies, soils were still considered to be geological phenomena, and their properties were

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assumed to be correlated directly with geological formations or other geological units. Emphasis was placed upon the origin of soil materials as a key to chemical differences affecting soil fertility and upon soil texture and soil color as the two most obvious physical properties indicative of differences influencing crop growth.

The units of soil classification were the soil type, the soil class, and the soil series. The soil type was considered to be the fundamental unit in both the classification and the mapping of soils. As is done today, many factors were considered in its definition. These included texture, structure, organic matter content, origin, color, depth, drainage, topography, native vegetation, and natural productivity. Soil class was defined essentially in terms of the present-day definition. To illustrate the concept of the soil series, the following definition is taken from the *Soil Survey Field Book* (10) published in 1906:

"*Soil series.* It has been found that in many parts of the United States a given set of soil classes are so evidently related through source of material, method of formation, topographic position, and coloration that the different types constitute merely a gradation in the texture of an otherwise uniform material. Soils of different classes that are thus related constitute a series. A complete soil series consists of material similar in many other characteristics, but grading in texture from stones and gravel on the one hand, through the sands and loams, to a heavy clay on the other."

In *Soils of the United States* (11), published in 1910, the known soil series were grouped into thirteen great soil provinces and shown on a map. The soils peculiar to the individual provinces were assumed to owe their characteristics to operation of the following geological agencies or processes; climate, heat metamorphism, ice, rushing glacial water, wind attrition, lakes, oceans, rivers, topography, and volcanoes. This emphasis on the origin of soil material brought together soils having very different characteristics. For example, soils in northern Montana, in Michigan, in Maine, and in parts of Mississippi were placed in the same category.

It is unfair to imply that the early field men failed to observe important profile features. Early reports indicate that recognition was given to important differences in drainage and color that were not directly related to differences in geological material. The difficulty lay in lack of a clear concept or framework in which to place such observations.

*The soil as something more—1912-1913.* In November 1912 appeared a bulletin that apparently was received with little or no enthusiasm at that time, but which has stood the test of time, and seemingly deserves to rank as a classic. This publication was *A Study of the Soils of the United States* (2) by George N. Coffey, a scientist in the Division of Soil Survey. Coffey's statement on the need for soil classification is distinctly appropriate, even for today. It reads, in part, as follows:

"In the study of soils, as well as any other subject which has to do with a large number of individuals, classification is of the utmost importance in order that the various and complex relations may be shown as far as practicable. . . . No more fundamental work than the proper classification and correlation of the soils of the country confronts soil investigators today, for this information is essential to the final solution of some of the most important questions with which they have to deal."

Coffey carefully reviewed and summarized the various systems of soil classification that had been attempted throughout the world. He pointed out that a classification of soils based only on geological criteria failed to consider the biological and climatological factors of soil formation. Likewise he condemned, as inadequate, systems of classification based only on limited physical or chemical features. He thought that a classification of soils according to native vegetation was going at the matter backwards.

In formulating a basis for his own classification, Coffey was influenced by the work of Dokuchaiev in Russia. Further, he foreshadowed Marbut in pointing out that it was necessary to recognize inherent differences in the soil itself, and to consider soil as an independent natural body having a definite genesis and distinct nature of its own. Moreover, he drew attention to the interdependent nature of soil characteristics and to the fact that the relative importance of any one characteristic changed with a change in another

interdependent characteristic. Humus, lime, and clay were emphasized by Coffey as of great importance, and he decided therefore that his major divisions in soil classification should emphasize differences in the proportions of these constituents. He was convinced that these soil characteristics resulted largely from differences in leaching and corresponded closely to climatic regions.

It is not clear why Coffey's ideas were not accepted or why he never received acclaim for his independent contribution, but probably his departure from the concepts formulated and held by Whitney and his early resignation from the Bureau of Soils are a partial explanation.

Within the year following Coffey's publication, Bulletin 96 of the Bureau of Soils—*Soils of the United States*—appeared (4). This brought together in a single volume all the recognized soil types and soil series in the United States, and was the final word in classification. Bulletin 96, by and large, continued to treat soils from the geological point of view and emphasized the source and agency of formation of soil material. There is little indication that soils should be classified on the basis of their own characteristics, although one sentence stands out as a prophecy of things to come—"Surface material becomes soil through the combined action of weathering and life."

*The soil as a natural body—1921-1935.* No further important developments affecting the fundamental concept of the soil were reported until Marbut's paper, *The Contribution of Soil Surveys to Soil Science* appeared in 1921 (5). This was not an inactive period in soil survey, however, since field techniques in soil mapping were improved, new areas were investigated, and particularly since it was a period of growth and study for Marbut, who had been placed in charge of soil survey work in 1913. This period witnessed the evolution of Marbut, geologist, to Marbut, soil scientist. Aside from obtaining first-hand knowledge of many of the soil types in the United States, Marbut read and translated Glinka's *Die Typen der Bodenbildung* from the German. It was during this period that Marbut crystallized, in his own mind, the differentiating attributes of a soil as a developed natural body. Soils could not be explained wholly on the geological basis, on the climatic basis, or by the natural vegetation. Topography (and drainage) and time were additional factors in soil formation. The profile was the unique feature of the soil that characterized it as a natural body.

In his paper on soil surveys and their contribution to soil science, Marbut wrote:

"As formerly, soils are differentiated into textural units, this applying to the texture of the surface horizon; or the upper two horizons where the surface horizon is extremely thin. Texture units are further subdivided on the basis of those features of the soil profile that do not concern the texture of the surface horizons. The units or groups of units based on features of the soil profile are designated as soil series. The features of the soil profile that are now regarded as significant and in constant use as bases for differentiation are:

1. Number of horizons in the soil profile.
2. Color of the various horizons, with special emphasis on the surface one or two.
3. Texture of the horizons.
4. Structure of the horizons.
5. Relative arrangement of the horizons.
6. Chemical composition of the horizons.
7. Thickness of the horizons.
8. Geology of the soil material.

"Other features, not yet used, but features that will become important in the future, at least much more so than now, are what I may call the physical constants of the various soil horizons as well as of the soil as a whole. By these is meant water-holding capacity, penetrability, etc.

"It would be unsafe to predict that no other features, not now known, would ever become important as bases of differentiation. Personally, I am of the opinion that others will be discovered and sincerely hope they may be. I am of the opinion that we have not yet

discovered all the important features of the soils or all of the characteristics of soils worthy of consideration in soil definition and soil mapping."

In 1922, in a paper *Soil Classification* (6), Marbut added "the thickness of the true soil" and "the character of the soil material" to the eight features listed the previous year to be used to characterize the soil profile. Soil types of a given name were considered to be uniform in all respects, and soil series in all respects except the texture of the surface horizon, or the upper two horizons if the upper one was extremely thin. Marbut likened soil classification to the established systems of classification in the plant and animal kingdoms. The soil type was comparable to species; the series, to families; and broader groups were comparable to the order. In all of this, Marbut was primarily concerned with mature soils—those which definitely expressed the impact of environmental factors through soil-forming processes. He dismissed *soil province* as a geographic term not within the realm of soil classification.

Thus by 1922, Marbut had formulated his concept of soil as a natural body and had outlined the framework for a soil classification system which was presented in greater detail in later papers, particularly in the *Atlas of American Agriculture* (7). Six categories were eventually recognized—soil types, soil series, local environment groups (family), great soil groups, inorganic colloid composition groups, and solum composition groups. This last or highest category consisted of *Pedalfers* and *Pedocals*—two new terms.

Marbut's emphasis on the soil as an independent natural body characterized by its unique profile greatly stimulated interest in soil morphology, soil genesis, and soil classification. Unknown features were observed for the first time. Old questions were answered and new ones uncovered. Of such was the new science of soil.

*The soil as a natural geographic body.* In more recent years the concept of soil as a natural body with its own developed morphology has been expanded so that soil is now definitely considered to be a geographic natural body. Not only does the fundamental soil unit—the soil type—possess a unique soil profile, but it also has geographic extent and surface configuration and thereby forms an integral part of the landscape. In other words soil types are "little landscapes." The following quotation from the U. S. Department of Agriculture 1938 Yearbook (1) is illustrative:

"Since the soil is the combined product of climate, living organisms, relief, parent material, and age, each different combination of these factors will produce a different soil. If all variations in each factor were measurable, and had measurable influences on the soil, individual soil types would be so numerous that they would occupy points. In a strict sense each soil profile is individual; no two are identical in every detail. Since there can be some range in the environmental factors without producing measurable differences in the soil, each soil type occupies an area rather than a point. The size and shape of individual areas varies greatly in different places."

An important result of the change in the concept of soil to that of a natural geographic body having three dimensions has been to make it possible to relate the results of research in the laboratory and greenhouse more definitely and directly to farms and other land areas. Chemical data are obtained from soil profiles sampled at specific points, whereas crop yield data and soil management practices apply to plots and fields. Recognition of the geographic character of the soil type has greatly accelerated interchange of such information. Though undoubtedly many persons had understood in a general way the geographic nature of the soil type, little progress had been made in bringing together the results of the laboratory and of the soil survey and applying them to individual farms.

Along with the crystallization of the concept that soils are definitely geographical bodies came the realization of the need for a system of soil classification that covered all soils, regardless of their relative degree of development. Since Marbut's scheme classified only mature soils in the upper three categories, and the terms *Pedalfers* and *Pedocals* did not apply to all soils, such as Degraded Chernozems, Alluvial soils, and Lithosols, a shift was made to zonal, intrazonal, and azonal as the subdivisions of the top category—the order—in the 1938 Yearbook. In addition, suborders were named in terms of geographical regions,

and the family concept was changed to a group of soils having similar profiles intermediate between the series and the great soil group.

#### PRESENT TRENDS

Reference to the previous papers in this issue of SOIL SCIENCE and to the article *Soil Classification* in the 1938 Yearbook will give the current concepts of soil classification in the United States except as they may be modified by present trends and actual practice. The remainder of this paper deals with these two aspects of the situation and with research needs.

Along with the changing concepts of categorical soil units outlined above, changes in techniques for identifying and mapping cartographic soil and land units—types, phases, complexes, associations, and miscellaneous land units—have been developed. For example, aerial photographs have replaced base maps made with the plan-table traverse as a basis for plotting soil boundaries in the field. This has resulted not only in more accurate base maps, but also in more accurate and detailed plotting of soil boundaries on the improved base map. With more accurate delineation of soil boundaries made possible, there also developed a sense of responsibility for more careful definition of the mapping units themselves and an increased appreciation of the meaning of soil phases, soil types, and soil series as they affect operations on and management of individual fields and farms. This has been true not only of the soil surveyor but of other workers in agricultural extension and research. These tendencies to examine soil conditions more minutely have resulted in more common use of the phase to bring out differences in the soil, or in the landscape of which the soil is a part, that are of importance in land use but which are not differentiating characteristics of the soil in the natural landscape under the natural vegetation. Slope, stoniness, and degree of accelerated erosion are examples. Closer scrutiny of the soil itself has led to an increased application of Marbut's ten requirements for a soil unit. The result has been a great increase in the number of recognized series. For example, such properties as thickness, water-holding capacity, and pH of individual soil horizons have come to have greater importance as criteria for soil classificational purposes than ever before. Admittedly, increased knowledge of soil science has led to some minor changes in the exact meaning of Marbut's criteria. For example, *chemical composition* now includes data on total exchange capacity, kind and amount of exchangeable ions, and percentage saturation. Physical characteristics, as well as mineralogical, are now more definitely understood by *geology of the soil material*.

Increasing knowledge of soils throughout the world, and especially in the tropics, is focusing attention on the inadequacies of the classification scheme presented in the 1938 Yearbook. Present knowledge is still too limited, however, to permit development of the perfect system with mutually exclusive categories. There are yet many soils to be seen and fitted into their proper places beside the other units.

Concurrent with the refinement in the definition of soil series, greater emphasis is being placed on the permissible range in the defined differentiating char-

acteristics of a soil, since it is realized that no two profiles can be considered identical in every respect. It may be added that soil phases are recognized as variations within the definitions of the soil type rather than as variations apart from the soil type.

More definite measurements and terms are being employed to record soil characteristics. Recently defined terms of structure, slope, drainage, coarse fragments, and consistence, and use of the color chart to record soil color are examples.

There is a realization that probably the geological and time factors have been underemphasized in relation to the other soil-forming factors in explaining many soil features. For example, it is now questioned whether the hardpan of the Leonardtown soil can be explained entirely in terms of eluviation and illuviation.

With the change from rather general to detailed mapping, stimulated in part by the preparation of yield estimates, has come also recognition for more careful inspection and correlation work, if categorical soil units are to be defined properly, soil boundaries are to be drawn accurately, and the mapping units interpreted adequately for agronomic, engineering, and other purposes. This is in rather marked contrast to the earlier days, when travel by soil scientists for purposes of studying questions of correlation was limited.

#### IMPERFECTIONS DUE TO CHANGING CONCEPTS

As long as soils were considered to be primarily geological bodies, variations in profile features, except for texture and color, gave little concern in classification. Because emphasis was placed on origin of soil materials, and also because a complete series was considered to include gravelly types on the one hand and clays on the other, a wide range of profiles was allowed within one series. With the introduction of the concept of a soil profile and the reference to ten essential profile features, the concept of a series was greatly altered. Many of the older and widely published series were seen to be too broadly and loosely defined. Precedent in the use of names, especially those used and published over wide areas and for long periods, made it difficult to revise series in accordance with the principles laid down by Marbut. In fact, at the present time, 27 years later, it is still exceedingly difficult to obtain agreement on the need to recognize new series which split the older established ones. Our practice in this respect sometimes falls far short of the discipline we proclaim to follow.

Another inconsistency between theory and practice is the failure to recognize new soil series because of their limited geographical extent, even though there may be no question regarding their uniqueness as a classification unit. In the past, these have been named as phases of the most closely related series. The answer to this conflict seemingly revolves about which is to have preference: logical principles of classification or practical aspects associated with the need to keep the number of series names to a minimum. Recently, it was proposed that some minimum requirement of geographical significance be added to Marbut's list of criteria, along with a proposal to establish a new unit—the variant—in which to place such uncommon soils. Except for its limited geographical extent

or significance, the variant would possess sufficient unique soil character to qualify as a type of a separate series.

Although it has been said for 25 years or more that the textural name of a soil type refers to the texture of the surface layer, or layers, equivalent to 6 inches or plow depth, actually the textural names of the coarser-textured soils of southeastern United States have referred to an assumed effective texture based on depth to an underlying heavier substratum. In many instances, for example, the surface texture of Norfolk sandy loam is actually a loamy sand. Although the inconsistency of this practice is acknowledged, much resistance is met to recently suggested changes because the old names have been used and understood for many years.

#### SOME RESEARCH NEEDS

More complete knowledge of the physical, chemical, and mineralogical properties of all the recognized soil series is needed in order to characterize them more fully and to evaluate better the relationships among them, particularly in respect to their classification and their productivity under specified management practices. The soil sampling, morphological description, and laboratory work required to obtain these data is in itself a big order in soil research. For example, there is still much to learn regarding the character and degree of base saturation of the colloids of the many soil series that have been established and are being proposed. Another important job is to determine the character and distribution of the major types of clay minerals in different soils in order to see the relationships that exist between types of profiles and amount and character of clay minerals. A part of this general assignment is to obtain working tools and methods whereby small but significant changes in such features as structure, porosity, and consistence can be measured.

The present system of soil classification in recognizing zonal, intrazonal, and azonal orders requires that soil scientists distinguish the developed or genetic features of the soil from those that have been inherited from the parent material. Moreover, a knowledge of the genesis of soil features is used to some extent in classifying soils into great soil groups and suborders. This is in contrast to the establishment of soil series, types, and phases where morphological and other observable features have been used almost exclusively as the basis. In addition, the significance of the various aspects of each feature of a given soil must be understood if the soil is to be completely characterized, classified, and given interpretive meaning for possible uses and responses to management. Our present knowledge falls far short of these requirements.

Color furnishes an excellent example of a property that may be either acquired or inherited. Further knowledge is needed regarding the relative importance of different colors as a basis for establishing soil series and grouping them into families and the higher categories. It is also important to know in what soils these differences of color are particularly important. Relationships of color to the kind and amount of organic matter and to drainage conditions in different soils are illustrations of unfinished research.

There is need to add to the knowledge of soils by investigating unknown soil areas in order to complete the natural system of soil classification. Such knowledge will serve also to check the adequacy of the present system, and possibly help provide a basis for the selection of criteria to differentiate the higher categories—a task which has not been done, as Cline points out in his contribution to this symposium. In checking the adequacy of the present system, one should bear in mind that each unit and each category in the classification has several boundaries with other units or categories, so that whenever a change is made in the definition of one unit or category, the definitions of the adjoining units or categories are also affected. Changing a unit in classification is a good deal like throwing a stone into a pool of water; the ripples go out in all directions.

An urgent need at present is a grouping of soil series into families. At the level of the family the two ends of the classification system, which have been developed somewhat differently and independently, meet. There are difficulties to be resolved in grouping the objectively defined types and series into families that will fit neatly into the great soil groups, which are defined partly on the basis of genesis and geography.

Research is needed for the further definition and mapping of slope classes. At present undue emphasis seems to be given to slope gradient as the basis for slope classification at the expense of other slope characteristics, which include length of slope, shape of slope (concave or convex), relative smoothness or roughness of surface configuration, direction of slope and resulting exposure to the sun. All of these features are related to adaptability of crop plants, rate of runoff, and erosion, and are important in mapping slope phases designed to indicate differences of slope significant to the use and management of soil areas.

Texture designation has many unsolved angles. For example, by present definition, a soil with 90 per cent kaolinitic clay cannot be classified satisfactorily either as a clay or as a loam. Despite textbook definitions to the contrary, common usage of textural terms implies some degree of soil behavior in an agronomic sense as well as particle-size distribution. The present texture triangle or chart is confined largely in its use to soils of the temperate regions. There is a need to evaluate the activity of clay and modify the figure for the content of clay by some correction factor if there is to be a comparable relationship between content of clay and textural name for all soils. There is also more to be learned about the relationships between content of organic matter and textural grade.

More attention should be given to relationships between the processes affecting geomorphical change and those of soil formation. Seemingly there is an implied assumption that soil formation takes over, independently of, and at the end of a period of, geomorphological change. Of course, these processes are going on at the same time, but with relatively varying degrees of intensity in different places from time to time. Associated with this subject is the study of buried soils or those of older landscapes and the relations that exist between the older profiles and the more recent ones that have developed from, in, or over them. Such studies may have a direct bearing on an understanding of the genesis of various



indurated horizons and claypan layers. Moreover, it is possible that many of the B horizons commonly explained by illuviation processes may be related rather definitely to old land surfaces. Recent observations in the Coastal Plain suggest this.

In conclusion, we wish to emphasize the need to bring together the results of various fields of soil research. Data from the laboratory—chemical, mineralogical, physical, and biological—must be related properly to results from the greenhouse and the field plot, and to the facts of soil morphology and soil geography. In addition, it is necessary to consider the relationships of these data to the facts of past use, management, and crop response. This is true regardless of whether the direct purpose of the research is to explain soil genesis or to give to farmers recommendations for the use and management of the soils in their fields and pastures. For example, data on the available phosphorus content or pH values of soil samples have little significance without a knowledge of the geographic setting, soil morphology, and history of the use and management of the areas involved.

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# MINERALOGICAL COMPOSITION OF A HEATH PODZOL PROFILE

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In coastal regions and adjoining hills in the tropics a rather rapid rate of weathering prevails because of the warm and humid climate (16). In the temperate zones, weathering will be found only in soils wherein the mineral particles are being decomposed by humic and organic acids. The purpose of this paper is to obtain quantitative data about the degree of weathering in such temperate-zone soils, that is, in podzols.

Investigations into this matter have not been extensive. Cady (4) reported that hornblende and hypersthene weathered rapidly, whereas magnetite and garnet were only slightly attacked. Richard and Chandler (20) found that hornblende and hypersthene weathered rapidly in the A<sub>2</sub> horizon but were only slightly weathered in the C horizon. Matelski and Turk (18) reported that the least resistant mineral to podzol weathering was dark green hornblende, followed by gray-green hornblende, the opaque minerals, and garnet.

Besides strong disintegration of the minerals, the podzolization process is accompanied by formation of authigenic clay minerals; for example, according to Englehardt (9), kaolinite and boehmite were synthesized. Observations concerning this last mineral, however, were not decisive, as Englehardt was not sure of his results.

## THE PROFILE

A podzol profile on a heath in the Netherlands province of Drenthe was selected for study. Figure 1 shows roughly its composition. The dark, brittle iron hardpan just below the horizon of black sand and above the dark brown sand is especially noteworthy. From this typical podzol profile the following characteristic zones were sampled and analyzed: No. I, lead sand; No. II, black sand; No. III, brown sand; No. IV, yellow sand.

## METHOD OF ANALYSIS

One hundred grams of the sample was oxidized in a 1,000-ml. beaker with about 400 ml. water and 100 ml. 30 per cent hydrogen peroxide. The suspension was filtered through a membrane, and the residue was sieved on a screen with 60- $\mu$  openings. Of the material that passed through the sieve a mechanical analysis was made by the Atterberg method. Three separates were produced: 16-60  $\mu$ , and 2-16 $\mu$ , < 2  $\mu$ . The particles were dispersed with 0.1 N NH<sub>4</sub>OH. The material that did not pass through the sieve was further divided by sieves

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into the following separates: 60–210  $\mu$ , 210–500  $\mu$ , and  $> 500 \mu$ . The 16–60  $\mu$ , 60–210  $\mu$ , 210–500  $\mu$ , and  $> 500 \mu$  separates were examined microscopically; and the 2–16  $\mu$  and  $< 2 \mu$  separates, by means of x-rays.

The former were then separated by the Edelman method (8) into minerals with a specific gravity of  $> 2.9$  (separating liquid = bromoform)—the so-called “heavy” fraction—, and those with a specific gravity of  $< 2.9$ —the so-called

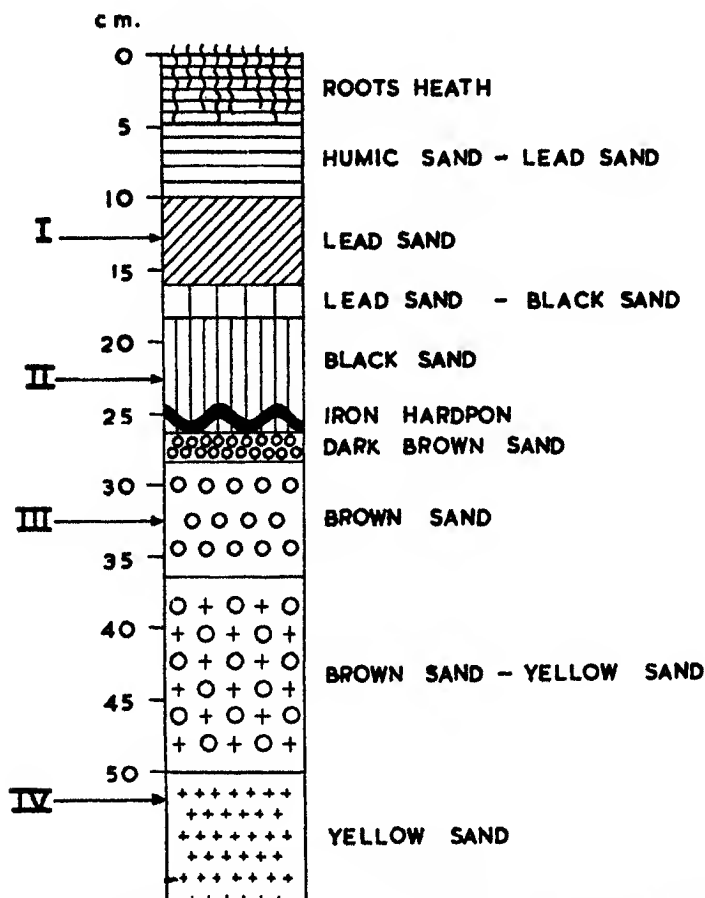


FIG. 1. PODZOL PROFILE ON A HEATH IN THE NETHERLANDS PROVINCE OF DRENTE

“light” fraction. The quantity of heavy minerals in each separate was then determined by weight, and the quantity of light minerals by subtracting the weight of heavy minerals from the weight of the total separate. After that, the kinds and the percentages of light and heavy minerals were determined by counting 100-odd minerals passing the dead center of a mechanical stage which was mounted upon a revolving stage of the microscope and which could be moved in two directions at right angles to each another.

According to Marshall (17) the results of a heavy mineral separation of a soil profile should be expressed on a volume basis and not on a weight basis. This is

because organic matter accumulates in the upper horizon and clay in the lower horizon, thus increasing the weight of a certain volume of soil. In the podzol here examined, however, clay was not predominantly accumulated in the lower horizons (I = 0.7 gm., II = 1.9 gm., III = 1.2 gm., IV = 0.4 gm. per 100 gm. of soil) and, further, by reckoning with inorganic particles, a volume basis was obtained.

According to Matelski and Turk (18) the surface areas of the minerals also should be measured and, for example, be expressed as maximum cross-sectional areas, because the shapes of the mineral particles differ. To reduce this error, the minerals were divided here by sieves and by the Atterberg method into several classes, which were counted separately. The percentages of the minerals thus counted were then multiplied by the total weight of the heavy or light fraction to which they belonged, to get the total weight of the minerals present in the soil. This calculation is not absolutely accurate, as the specific gravities of the different mineral particles occurring in the soil are not the same. It is sufficiently accurate, however, for practical purposes, as the object here is only to get an idea of the relative rate of weathering of different minerals under podzolic conditions.

All analyses were made in duplicate, and the results averaged. If the figures of the single observations deviated too much, the analysis was repeated.

#### RESULTS OF MECHANICAL ANALYSIS

The podzol profile has a fairly constant texture (fig. 2) when all figures are referred to 100 inorganic parts. The black sand (II) deviates slightly when the figures are referred to 100 gm. of soil. The reason for this deviation is the much higher humus content (loss on ignition in grams per 100 gm. of soil: I = 2.7, II = 12.9, III = 3.9, IV = 3.9).

The amount of heavy minerals increases considerably with depth. Apparently in the higher zones a very active decomposition has occurred. Further, it is rather remarkable that the percentage of heavy minerals is highest in the smaller-sized separates.

#### RESULTS OF MICROSCOPIC ANALYSIS

##### *Heavy minerals*

*Opaque.* The relative percentage of nontransparent minerals (mainly iron ore) decreases from the surface downward (tables 1 and 2). This is because these minerals are not easily dissolved and therefore accumulate in the more weathered zones. Some of them, however, have been dissolved, for, despite the smaller percentage in the deeper layers, the total amount in the yellow sand is higher than that in the lead sand.

*Tourmaline.* The relative percentage of tourmaline, like that of opaque minerals, decreases from the surface downward, and for the same reason. As the total amount in each zone is virtually the same, it may be concluded that but little tourmaline has been dissolved in the process of weathering.

*Zircon.* The relative percentages of zircon in the 210–500  $\mu$  and 60–210  $\mu$

separates are virtually the same in the four zones. In the 16-60  $\mu$  separate the percentage of zircon decreases from the surface downward. Thus apparently in the upper, more weathered zones, some concentration has taken place. The

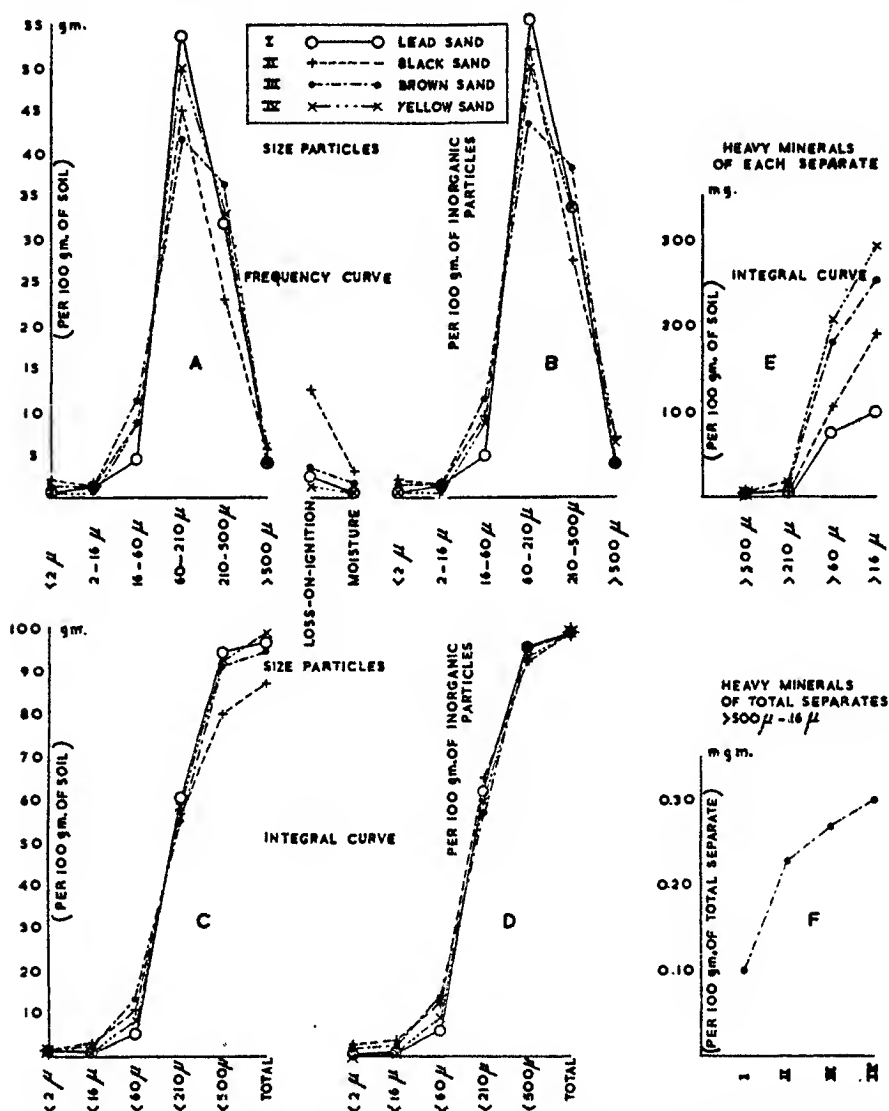


FIG. 2. RESULTS OF GRANULOMETRIC ANALYSES PLOTTED AS FREQUENCY CURVES (A, B) AND AS INTEGRAL CURVES (C, D); AMOUNTS OF HEAVY MINERALS IN EACH SEPARATE (E) AND IN TOTAL SEPARATES (F)

total amount increases with depth, from which it follows that some of this mineral has been dissolved in the process of weathering.

**Garnet.** The relative percentage of garnet increases with depth, as does the total amount in the separates. Apparently this mineral is dissolved in the process of weathering of the podzol profile.

TABLE 1

Results of microscopic analyses of heavy and of light minerals in  $>500 \mu$ , \*  $500 \mu - 210 \mu$ ,  $210 \mu - 60 \mu$ ,  $60 \mu - 16 \mu$  separates

SOIL HORIZON	SEPARATE, PER CENT†	UNIT OF MEASURE‡	HEAVY MINERALS (SP. GR. >2.9)										LIGHT MINERALS (SP. GR. >2.9)					
			Opaque	Tourmaline	Zircon	Garnet	Rutile	Staurolite	Epidote	Saursurite	Amphibole	Other minerals	Total	Muscovite	Feldspar	Quartz	Other minerals	Total
500 — 210 μ separate																		
I	32.3	per cent	54	21	2	16	—§	5	—	1	—	1		—	2	97	1	
		mgm.	5.4	2.1	0.2	1.6	—	0.5	—	0.1	—	0.1	10	—	646	31321	323	32290
II	23.4	per cent	48	17	2	24	—	3	1	3	1	1		—	4	95	1	
		mgm.	5.3	1.9	0.2	2.6	—	0.3	0.1	0.3	0.1	0.1	11	—	936	22220	234	23389
III	36.5	per cent	38	12	3	26	—	3	4	11	2	1		—	6	93	1	
		mgm.	6.1	1.9	0.5	4.1	—	0.5	0.6	1.8	0.3	0.2	16	—	2189	33930	365	36484
IV	32.8	per cent	34	8	3	26	—	2	6	16	4	1		—	6	93	1	
		mgm.	5.1	1.2	0.5	3.9	—	0.3	0.9	2.4	0.6	0.1	15	—	1967	30490	328	32785
210 — 60 μ separate																		
I	54.3	per cent	52	8	10	12	4	3	8	1	1	1		—	7	92	1	
		mgm.	36.9	5.7	7.1	8.5	2.8	2.1	5.7	0.7	0.7	0.7	71	—	3796	49891	542	54229
II	45.4	per cent	46	6	11	14	2	2	14	1	3	1		—	12	87	1	
		mgm.	45.1	5.9	10.8	13.7	1.9	1.9	13.7	1.0	2.9	1.0	98	—	5436	39413	453	45302
III	41.7	per cent	28	5	11	19	1	2	23	2	8	1		0.5	11	88	0.5	
		mgm.	44.2	7.9	17.4	30.0	1.6	3.2	36.3	3.2	12.6	1.6	158	208	4570	36557	208	41542
IV	49.5	per cent	20	3	11	21	tr	2	26	2	14	1		1	12	87	tr	
		mgm.	37.2	5.6	20.5	39.1	tr	3.7	48.3	3.7	26.0	1.9	186	493	5918	42903	tr	49314
60 — 16 μ separate																		
I	4.6	per cent	52	2	23	1	10	—	10	1	—	1		2	22	75	1	
		mgm.	9.4	0.4	4.1	0.2	1.8	—	1.8	0.2	—	0.2	18	92	1008	3437	46	4582
II	8.6	per cent	40	2	18	5	9	—	18	2	5	1		3	21	75	1	
		mgm.	31.2	1.6	14	3.9	7	—	14	1.6	3.9	0.8	78	256	1790	6391	85	8522
III	11.0	per cent	37	1	17	8	8	—	20	2	6	1		4	21	74	1	
		mgm.	28.9	0.8	13.3	6.2	6.2	—	15.6	1.6	4.7	0.8	78	437	2294	8082	109	10922
IV	8.8	per cent	31	1	16	9	7	—	24	2	9	1		6	22	72	tr	
		mgm.	23.6	0.8	12.2	6.8	5.3	—	18.2	1.5	6.8	0.8	76	523	1919	6281	tr	8724

\*  $>500 \mu$  Separate:

Total separate, per cent: I = 3.9, II = 6.1, III = 3.8, IV = 6.6.

Total heavy minerals in separate, mgm.: I = 3, II = 4, III = 3, IV = 5.

Total light minerals in total separate, mgm.: I = 3,897, II = 6,096, III = 3,797, IV = 6,596.

Kinds and amounts of heavy minerals (mostly iron oxides) and light minerals (mostly quartz) not determined.

† Of 100 gm. soil.

‡ Per cent of counted particles and mgm. of each separate per 100 gm. soil.

§ — Indicates virtual absence of mineral.

*Rutile.* The relative percentage of rutile decreases with depth, but the total content of the different zones is virtually the same. From this it follows that a relative concentration takes place in the more weathered zones.

*Staurolite.* The relative percentage of staurolite decreases slightly with depth, whereas the total content increases slightly. Thus, podzolic weathering dis-

TABLE 2  
Results of microscopic analyses of heavy and of light minerals in total 500 - 16  $\mu$  separates

SOIL HORIZON	HEAVY MINERALS											LIGHT MINERALS				
	Opaque	Tourmaline	Zircon	Garnet	Rutile	Staurolite	Epidote	Saussurite	Amphibole	Other	Total	Muscovite	Feldspar	Quartz	Other	Total
<i>A—mgm. in total 500 — 16 <math>\mu</math> separates per 100 gm. of soil</i>																
I	51.7	8.2	11.4	10.3	4.6	2.6	7.5	0.9	0.7	0.9	99	92	5450	84649	911	91101
II	81.6	9.4	25.0	20.2	8.9	2.2	27.8	2.9	6.9	1.9	187	256	8162	68024	772	77213
III	79.2	10.6	31.2	24.0	7.8	3.7	52.5	6.6	17.6	2.6	252	645	9053	78569	682	88948
IV	65.9	7.5	33.2	49.8	5.3	4.0	67.4	7.6	33.4	2.8	277	1016	9804	79674	328	90823
<i>B—per cent per 100 particles in total 500 — 16 <math>\mu</math> separates</i>																
I	52.2	8.3	11.5	10.4	4.6	2.6	7.6	0.9	0.7	0.9	99.7	0.10	6.0	92.9	1	100.0
II	43.6	5.0	13.4	10.8	4.8	1.2	14.9	1.5	3.7	1.0	99.9	0.33	10.6	88.1	1	100.0
III	31.4	4.2	12.4	16.0	3.1	1.4	20.8	2.6	7.0	1.0	99.9	0.73	10.2	88.3	0.8	100.0
IV	23.8	2.7	12.0	18.0	1.9	1.4	24.3	2.7	12.0	1.0	99.8	1.12	10.8	87.7	0.4	100.0
<i>C—mgm. per 100 particles in total 500 — 16 <math>\mu</math> separates</i>																
I	56.7	9.0	12.5	11.3	5.0	2.9	8.2	1.0	0.8	1.0	108.5	101	5976	92817	999	99891
II	105.4	12.1	32.3	26.1	11.5	2.8	35.9	3.8	8.9	2.5	244.5	331	10545	87886	997	99758
III	88.8	11.9	35.0	45.2	8.7	4.1	58.9	7.4	19.7	2.9	282.5	723	10149	88082	765	99717
IV	72.3	8.2	36.4	54.7	5.8	4.4	74.0	8.3	36.7	3.1	304.1	1115	10762	87458	360	99696
<i>C<sub>1</sub>—Same as C but calculated on lead sand</i>																
I	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
II	1.9	1.3	2.6	2.3	2.3	1	4.4	3.0	11.1	2.5	2.3	3.3	1.8	0.9	1	1
III	1.6	1.3	2.8	4.1	1.7	1.4	7.1	7.4	24.6	2.9	2.6	7.1	1.7	0.9	0.8	1
IV	1.3	0.9	2.9	4.8	1.2	1.5	9.0	8.3	45.9	3.1	2.8	11.0	1.8	0.9	9.4	1

solved some of this mineral, causing a relatively higher concentration in the upper, more weathered zones.

*Epidote.* The relative percentage of epidote distinctly increases with depth, as does the total amount. This shows active decomposition by podzolic weathering. It is noteworthy that epidote is associated mostly with the 60-210  $\mu$  and 16-60  $\mu$  separates.

*Saussurite.* The relative percentage of saussurite (strongly weathered epidote)



clearly increases with depth, especially in the 210–500  $\mu$  separate, as does the total amount. Thus it follows that part of this mineral has been dissolved.

*Amphibole* (green). The relative percentage of amphibole increases markedly with depth, and the total amount increases in the same direction. This points to a particularly strong weathering of the mineral.

The higher amount of opaque, tourmaline, and rutile in the black and brown sand as compared to the lead sand and the yellow sand and of zircon in the black sand as compared to the lead sand may be due to the fact that these minerals, of which the opaque may occur in long, ragged forms, and of which the other three are characterized by long forms (prismas), are carried downward with the rains in the shape of very small needles.

TABLE 3  
*K<sub>2</sub>O content of feldspars in podzol horizons\**

SOIL HORIZON	TOTAL K <sub>2</sub> O	K <sub>2</sub> O SOLUBLE IN 25 PER CENT HCl	K <sub>2</sub> O INSOLUBLE IN 25 PER CENT HCl	TOTAL FELDSPAR PARTICLES IN 16– 500 $\mu$ SEPARATES	K <sub>2</sub> O CONTENT (CALCULATED) OF FELDSPAR IN 16– 500 $\mu$ SEPARATES
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>gm.</i>	<i>per cent</i>
I	0.340	0.008	0.332	5.450	6.1
II	0.590	0.019	0.571	8.161	7.0
III	0.750	0.026	0.724	9.051	8.0
IV	0.870	0.038	0.832	9.803	8.5

\* Analyses obtained from chemical research of the soil samples by J. ten Have, chief analyst of the Institute.

#### *Light minerals*

*Muscovite*. The relative percentage of muscovite increases considerably with depth, as does the total content. This points to marked weathering by humic and organic acids.

*Feldspar*. The relative percentage of feldspar (albite, oligoclase, andesine, microcline, orthoclase) is fairly constant, except in the lead sand, where it is smaller. The total amount increases only slightly with depth in the black and brown sands. The black sand contains a considerable amount of organic matter, leaving less room for inorganic particles. A slight decomposition of the feldspar in the black and brown sand and a stronger decomposition in the lead sand are indicated.

When the percentage of K<sub>2</sub>O in the feldspar is computed<sup>2</sup> from the total percentage of K<sub>2</sub>O in the soil and the total amount of feldspar in the 16–500  $\mu$  separate, an approximate figure is obtained for each of the different zones. The results are summarized in table 3. From these figures it may be concluded that, in general, the potassium content of the feldspar decreases considerably from the lower zones upward, especially in the black and lead sands. This points to the

<sup>2</sup> The quantity of K<sub>2</sub>O taken to compute the K<sub>2</sub>O content of the feldspar includes only some K<sub>2</sub>O present in 25 per cent HCl-extracted muscovite and some K<sub>2</sub>O as illite in the <16  $\mu$  separates.

fact that podzolic weathering is a selective process as regards the kind of feldspar being decomposed; in the black sand and the lead sand especially, relatively more potassium feldspar (orthoclase, microcline) is dissolved than sodium and calcium feldspar (albite, oligoclase, andesine).

**Quartz.** The relative percentage of quartz is nearly equal in all samples except in the lead sand, where it is somewhat higher. The total amounts are nearly equal except in the black sand, which contains a great amount of humus, thus leaving less room for other components. But when these data are calculated on total inorganic particles, this difference also vanishes (table 2 C<sub>1</sub>). These results indicate that scarcely any of the quartz is dissolved by the podzolic weathering process and that this mineral has concentrated in the strongly weathered lead sand. The percentage of quartz in the 16–60  $\mu$  separate containing feldspar and muscovite is evidently lower than that in the coarser separates in which muscovite is virtually absent.

#### *Weathering of heavy and light minerals*

Figure 3 shows how the principal minerals of the podzol profile are attacked by humic and organic acids. Even the most resistant mineral does not escape this process. Druif (7) also drew attention to this phenomenon in his research into the weathering of minerals under tropical conditions.

It is remarkable also that development of a great number of long needles is restricted to minerals that weather readily, like amphibole (fig. 3, Nos. 1 and 2). The less readily weathering minerals have a smaller number of needles, for example, epidote (Nos. 3 and 4) and feldspar (Nos. 5 and 6). Those very resistant to weathering, such as garnet (Nos. 7 and 8) and especially zircon (Nos. 9 and 10), develop shapes very similar to those of the unweathered minerals. Still more resistant minerals, such as rutile (No. 11) and tourmaline, show only depressions, whereas quartz, the most resistant mineral, develops merely a cloudy surface. Muscovite, which weathers slightly less readily than amphibole, falls apart in very thin plates (No. 12), which eventually become perforated. Apparently the very resistant plates  $[(\text{Si}, \text{Al})_2\text{O}_5]$  occurring in this mineral withstand weathering longest.

Of the minerals discussed, the following contain plant nutrients in significant quantities<sup>3</sup>:

Tourmaline, 9.5 per cent  $\text{B}_2\text{O}_3$  and 10 per cent  $\text{MgO}$   
 Amphibole, 10 per cent  $\text{CaO}$  and 12 per cent  $\text{MgO}$   
 Muscovite, 1 to 2 per cent  $\text{MgO}$  and 9 per cent  $\text{K}_2\text{O}$   
 Garnet, 2 per cent  $\text{CaO}$  and 7 per cent  $\text{MgO}$   
 Epidote and saussurite, 20 per cent  $\text{CaO}$   
 Potassium feldspar (orthoclase, microcline), 12 per cent  $\text{K}_2\text{O}$  and 0.3 per cent  $\text{MgO}$   
 Sodium, calcium feldspar (albite, oligoclase), 0.1 to 8 per cent  $\text{CaO}$  and 0.2 per cent  $\text{MgO}$

Of these minerals, amphibole is most readily decomposed. The total contents of  $\text{CaO}$  and  $\text{MgO}$  in amphibole in the yellow sand are respectively about 3 and 4 mgm. per 100 gm. of soil. (This would be about 100 and 120 kgm. respectively

<sup>3</sup> Percentages are approximate.

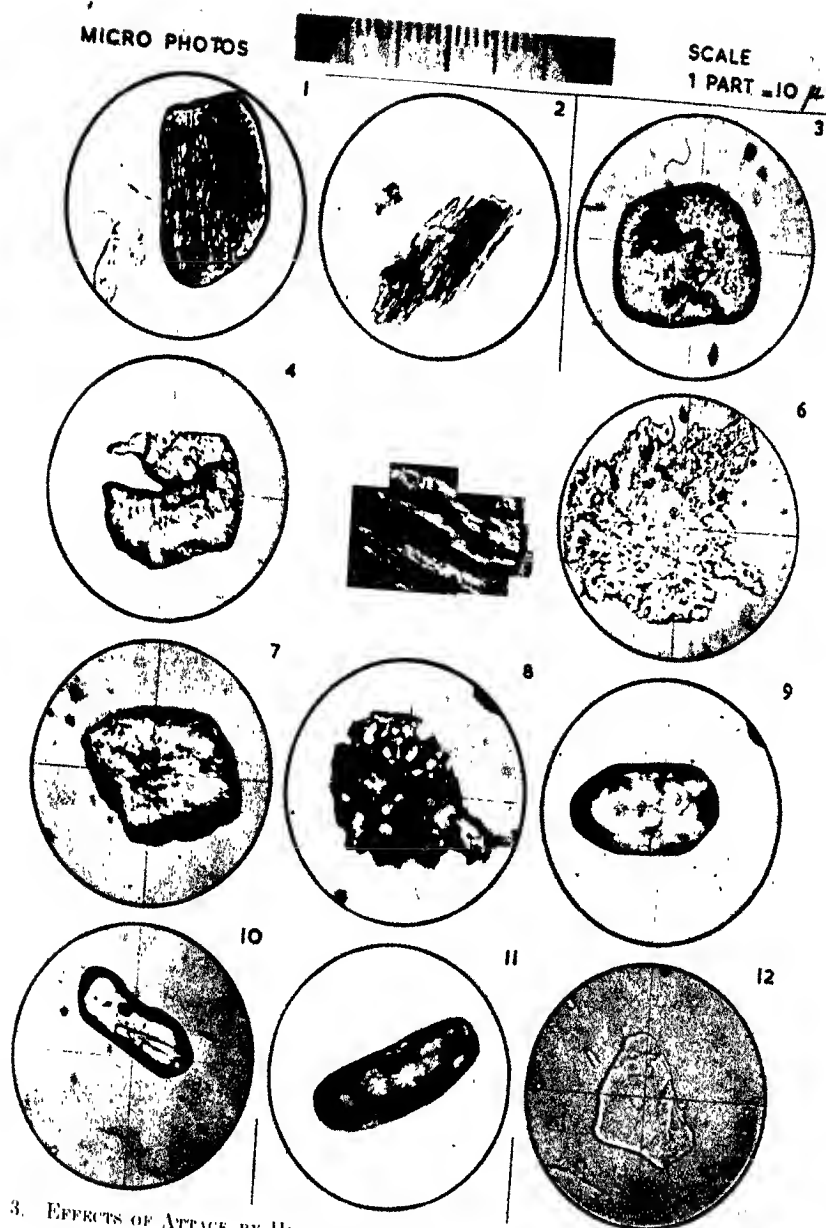


FIG. 3. EFFECTS OF ATTACK BY HUMIC AND ORGANIC ACIDS ON PRINCIPAL MINERALS OF THE PODZOL PROFILE

1. Amphibole, slightly weathered.
2. Same as 1, but more weathered.
3. Epidote, slightly weathered.
4. Same as 3, but more weathered.
5. Feldspar, slightly weathered.
6. Same as 5, but more weathered.
7. Garnet, slightly weathered.
8. Same as 7, but more weathered.
9. Zircon, slightly weathered.
10. Same as 9, but more weathered.
11. Rutile, weathered.
12. Muscovite, weathered.

per hectare to a depth of 12 inches.) Thus, in a year, only a very small amount of calcium and magnesium will become available for plants from amphibole; and, as several investigators have pointed out, development of a typical podzol profile requires approximately 1,000 to 2,000 years (22). This is true also for the other heavy minerals, garnet, epidote, saussurite, and tourmaline, all of which also contain CaO or MgO and decompose to a lesser degree than amphibole.

As the kind and the amount of the potassium and calcium feldspars were not determined separately, figures on amounts of CaO and MgO made available for the plant by the podzolization process cannot be given. The analyses show that the podzol contains a large amount of feldspar. According to chemical analysis, the total potassium content decreases in the course of decomposition from 0.870 per cent to 0.340 per cent. Thus only about 8 to 15 kgm.  $K_2O$  per hectare-12-inch-depth becomes available yearly. Consequently, significant quantities of potassium cannot be expected to become available for plants from potassium feldspar (orthoclase, microcline) under normal weathering conditions in the type of soil analyzed here.<sup>4</sup>

The analyses further show that in the yellow sand, tourmaline, garnet, and saussurite occur mainly in the 210–500  $\mu$  separate; zircon and rutile, in the 16–60  $\mu$  separate; amphibole (green), in the 60–210  $\mu$  separate; and staurolite and epidote, in the 60–500  $\mu$  separate.

#### *Other minerals*

The following minerals occurred in very small amounts (totaling about 1 per cent of each separate): kyanite, andalusite, glaucophane, corundum, titanite, sillimanite, allanite, piedmontite, hydrargillite, and augite. Augite was found mainly in the brown sand and in the yellow sand.

#### RESULTS OF X-RAY ANALYSIS

The 2–16  $\mu$  and < 2  $\mu$  separates were mixed with glycerine (15) to form a paste and were dried, in an oven at  $\pm 170^\circ C.$ , just enough to pass a 60  $\mu$  sieve. They were then subjected to x-rays produced by a cobalt target,  $K_{\alpha 1-\alpha 2} = 1.787 \text{ \AA.}$ , in capillaries with a diameter of  $\pm 0.6 \text{ mm.}$  in a hydrogen-filled Favejée camera (10).

#### *2–16 $\mu$ separate*

All zones, especially the upper ones, consisted mostly of quartz. Other minerals in this separate were kaolinite, primarily in the lower horizons, and feldspar, mostly in the upper horizons. Muscovite occurred in negligible amounts in all horizons.

As the total amount of the 2–16  $\mu$  separate is greater in the upper horizons than in the lower, it may be concluded that quartz and feldspar were concentrated in the upper horizons and that some kaolinite and illite in a suspended state moved downward with the rains.

<sup>4</sup> This soil belongs to the petrological "A province" of the Quaternary period, according to Edelman (8). The soil classification is based on the fact that soils derived from different parent material have some outstanding mineral characteristics, so-called "guide minerals," which may be readily observed (6, 14).

< 2  $\mu$  separate

All zones, and especially the lead sand, contained quartz. Other minerals in this separate were kaolinite and illite, the latter mostly in the lower horizons. Both illite and kaolinite are common in the soils of the Netherlands, which are all derived from slates and shales containing these minerals. Only traces of feldspar and muscovite occurred in the < 2  $\mu$  separate. In earlier articles on clay minerals, muscovite is commonly said to occur in the < 2  $\mu$  separate, but not illite, which also belongs to the mica group. In the presence of other clay minerals, these two minerals differ very little. The following characteristic reflections on the photo are the only means of differentiating one from the other:

distinct lines		diffuse band	
Illite— $d = 3.09 \text{ \AA.}$ , $d = 2.82 \text{ \AA.}$		$d = 1.74 \text{ \AA.}$ , $d = 1.66 \text{ \AA.}$	
distinct lines		distinct lines	
Muscovite— $d = 3.18 \text{ \AA.}$ , $d = 2.97 \text{ \AA.}$		$d = 1.74 \text{ \AA.}$ , $d = 1.66 \text{ \AA.}$	

Minerals present in volcanic rocks, such as muscovite, cannot withstand weathering as particles < 2  $\mu$ . Quartz, an extremely resistant mineral, is an exception, as this may be found in considerable amounts in the < 2  $\mu$  separate. Only specific clay minerals such as illite, which are authigenic "secondary" minerals, can withstand weathering as particles < 2  $\mu$ .

The x-ray diffraction pattern of the yellow sand contained a typical line (that is, third line measured from the center  $d = 6.19 \text{ \AA.}$ ) representing a mineral which nearly completely dissolved when treated with 25 per cent HCl for 1 hour on a boiling water bath, and which consisted chiefly of aluminum. When the < 2  $\mu$  separate of the yellow sand was treated for 15 minutes with 5 per cent NaOH on a boiling water bath, however, this mineral was not dissolved. Further research showed that the reflection in question was caused by boehmite [ $\text{AlO}(\text{OH})$ ]. Bauxite occurs in nature locally in huge amounts in Suriname and France, and in the pure form contains mainly hydrargillite (also called *gibbsite*) [ $\text{Al}(\text{OH})_3$ ] and boehmite (also called *bauxite*).

Boehmite was thereupon artificially prepared by precipitating aluminum from a boiling aluminum chloride solution with ammonium hydroxide. The precipitate was then thoroughly washed and dried for several hours at  $\pm 105^\circ\text{C}$ .

The material thus prepared contained 76 per cent  $\text{Al}_2\text{O}_3$  equivalent to 89.4 per cent  $\text{AlO}(\text{OH})$  or 116.2 per cent  $\text{Al}(\text{OH})_3$ . The x-ray recording showed typical, though rather diffuse, boehmite reflections. Apparently, a mixture of boehmite and  $\text{Al}(\text{OH})_3$  gel was formed here. This preparation dissolved completely in 25 per cent HCl or 5 per cent NaOH when it was kept on a boiling water bath for 1 hour and 15 minutes respectively.

Natural boehmite, on the other hand, hardly dissolves in the above concentrations. The quantity dissolved in this case varies with the origin of the mineral respectively from 4–10 per cent and 1–6 per cent  $\text{Al}_2\text{O}_3$ . Apparently the resistance of boehmite to solvents is not constant, but increases with aging (development of larger crystals) as mentioned by Walden (23). Thus in the clay separate (< 2  $\mu$ ) of the yellow sand, boehmite that is only slightly aged occurs. It is a

mineral like kaolinite, which is formed in the process of weathering, that is, a so-called "secondary" clay mineral.

Finally, in the various samples of the  $< 2 \mu$  separate, the amounts of  $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  soluble in 25 per cent HCl and 5 per cent NaOH, when extracted for 1 hour and 15 minutes respectively on a water bath, were determined. The results are summarized in table 4. The figures show that from the black sand, the brown sand, and the yellow sand rather considerable percentages of sesquioxides dissolved in 25 per cent HCl. With the exception of the yellow sand, from which boehmite also was dissolved, most of the dissolved sesquioxides were in the form of amorphous hydroxide gels.

TABLE 4

*HCl-soluble  $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$  content and NaOH-soluble  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  content of  $< 2 \mu$  separate*

DESCRIPTION	SOIL HORIZON			
	I	II	III	IV
<i>&lt; 2 <math>\mu</math> Separate:</i>				
$\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$ soluble in 25 per cent HCl* . . . . . per cent	1	26	32	27
$\text{SiO}_2$ soluble in 5 per cent NaOH† . . . . . per cent	3	5	6	8
$\text{Al}_2\text{O}_3$ soluble in 5 per cent NaOH† . . . . . per cent	7	8	11	16
<i>&lt; 2 <math>\mu</math> separate per 100 gm. soil . . . . . gm.</i>	0.7	1.9	1.2	0.
<i>Calculated on total &lt; 2 <math>\mu</math> separate per 100 gm. soil</i>				
$\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$ soluble in 25 per cent HCl . . . . . mgm.	7	494	384	108
$\text{SiO}_2$ soluble in 5 per cent NaOH . . . . . mgm.	21	95		32
$\text{Al}_2\text{O}_3$ soluble in 5 per cent NaOH . . . . . mgm.	49	152	132	64

\* One hour on boiling water bath.

† Fifteen minutes on boiling water bath.

It is because of these gels that the x-ray recordings of the soil show more or less diffuse bands rather than sharp reflection lines like those of pure natural minerals. A recording made after extraction with 25 per cent HCl gives more distinct lines.

The various samples contain increasing percentages of silica gel from the surface downward. Calculated in absolute amounts, that is, on total particles  $< 2 \mu$  per 100 gm. of soil, the largest quantity of gels dissolved is from the black sand. De Vries (21, 22) also noted this particularly. It is in this zone that iron ore is deposited along the edge of the underlying brown sand (fig. 1). Here occurs the flocculation of gels, mainly iron hydroxide, which is less stable than aluminum hydroxide. The latter flocculates in a deeper layer, as evidenced by the fact that the  $\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$  extracted by 25 per cent HCl from the  $< 2 \mu$  separate of the yellow sand consisted mainly of aluminum, from the mineral boehmite.

Aaltonen (1, 2), de Vries (21, 22), and Bruin (3) also noted this difference in behavior of both kinds of gels in podzol profiles. The occurrence of a cemented iron ore layer and especially of the mineral boehmite points to circumstances

furthering dehydration, that is, a hot and dry period. This corroborates the opinion of Florschütz (11, 12) and Overbeek (19) that the podzols occurring in the Netherlands, especially those of so characteristic a type as the one analyzed here, are of fossile origin; that is, that they were formed in the moist atlanticum period, from about 5500 to 2500 B.C., and in the dry, hot subboreal period,<sup>1</sup> from about 2500 to 800 B.C.

Carroll (5) observed in lateritic soils of Western Australia an aluminum oxide mineral that was not readily attacked by NaOH solution, presumably, in his opinion, boehmite or diaspore. It was formed by partial desiccation of gibbsite during a recent very arid, hot period following the humid climate in which the laterite itself originally was formed.

#### SUMMARY

In the process of podzolization in a heath profile, horizons of humic sand with roots, lead sand, black sand, brown sand, and yellow sand are formed from top to bottom. Podzolization is accompanied by a strong attack of the soil minerals in the  $> 16 \mu$  separate by humic and organic acids.

The minerals do not all weather with equal readiness. Amphibole is subject to strong disintegration, followed in diminishing degree by muscovite, epidote, and saussurite. Garnet and zircon decompose with greater difficulty. Feldspar and staurolite decompose even less readily, and opaque, rutile, tourmaline, and quartz are very resistant to the action of humic and organic acids.

Minerals most resistant to change (opaque, staurolite, rutile, tourmaline, and quartz) will concentrate in relatively large quantities in zones subject to strong weathering, at the expense of the more readily weathering minerals (amphibole, muscovite, epidote, and saussurite), concentrations of which decrease. Zircon assumes an intermediate position, as its concentration remains virtually the same throughout; only in the  $16\text{--}60 \mu$  separate of this mineral, which of course is most subject to decomposition, does the concentration also increase.

It is rather remarkable that the amount of feldspar in reference to 100 parts of inorganic matter has shown marked decrease only in the lead sand. Apparently some of the feldspar, especially the potassium forms, can be decomposed only by a high concentration of humic and organic acids, whereas other feldspars, especially the calcium, sodium forms, are scarcely attacked at all. The latter were found to be concentrated in the  $< 16 \mu$  separate in considerable amounts together with quartz. In the  $< 16 \mu$  separate, kaolinite and especially illite moved downward in suspension, and consequently the lead sand consisted almost entirely of quartz and feldspar.

Moreover, as a result of strong disintegration of readily weathered minerals and concentration of minerals very resistant to weathering, the podzol was characterized by an authigenic mineral. Thus, in the  $< 2 \mu$  separate of the yellow sand, boehmite was found. This mineral was but slightly aged, as it was readily attacked by strong hydrochloric acid.

<sup>1</sup> According to archaeological observations of van Giffen (13), however, the subboreal period lasted from about 1400 B.C. to about 400 A.D.

It was further proved that the black sand of the podzol profile contained the largest total amount of free silicic acid and amorphous sesquioxides. This is also the horizon in which the iron hardpan was formed just above the brown sand.

The occurrence of the iron hardpan and especially of the mineral boehmite is further proof of the theory that podzols of the characteristic type analyzed are of fossil origin. They are not formed under present climatic conditions in the Netherlands.

In the  $> 16 \mu$  separates, tourmaline, garnet, and saussurite were present for the most part as 210–500  $\mu$  particles; zircon and rutile, mostly as 16–60  $\mu$  particles; amphibole as 60–210  $\mu$  particles, and staurolite and epidote as 60–500  $\mu$  particles.

With the exception of quartz, soil minerals were virtually absent from the  $< 2 \mu$  separate. The reason is that only the exceedingly resistant quartz and specific clay minerals can withstand the weathering process in particles of such small dimensions.

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# A COMPARISON OF THE REDDISH CHESTNUT SOILS OF THE UNITED STATES WITH THE RED-BROWN EARTHS OF AUSTRALIA

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A satisfactory system for world classification of soils is dependent on detailed study of profiles in all parts of the world. Although we are perhaps 50 or more years from attainment of such a system, it is worthwhile at this stage to compare soil profiles from different continents where detailed investigations have already been made. Two such continents are North America and Australia, where soil survey organizations are systematically studying soil profiles over areas of continental dimensions. The mapping units used for routine soil surveys on both continents are the series, type, and phase. Accurate descriptions of soil series, supported by analytical data, are available for areas of similar environment in both countries.

The great soil group includes a range of profiles produced throughout a broad zone where environmental conditions are generally similar. As the great soil group is characterized by the range of its member series, it is comparatively simple to compare great soil groups in different continents by presenting details of soil series that occur therein.

In selecting for study the American group of reddish chestnut soils and the Australian group of red-brown earths, the author has been guided in his choice by the large numbers of profile descriptions that are available for comparison. The method of presentation consists in marshaling these data and arranging them systematically together with certain collateral data; the conclusions are left largely to the reader. The advantage of this method is that the soil profile itself is the unit of study. Most previous attempts of this nature have used some form of climatic index as the basis for comparison. As climate is only one of the factors in soil formation, however, it is not surprising that such methods have only a limited application. It is worthwhile at this point to restate the general equation of soil formation:

$$\text{Soil} = f(\text{climate, vegetation, relief, age, parent rock})$$

The more passive factors of topography and parent rock are too often overlooked in soil classification. Where the soil profile is the basis for comparison, however, due weight is given to all factors because the profile is the final synthetic expression of all factors in its formation.

## GENERAL ENVIRONMENT

The reddish chestnut soils (25) are found in that part of continental United States between latitudes 28°N (southern Texas) and 38°N (southern Kansas)

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and between longitudes 98°W and 102°W. The red-brown earths of continental Australia (18) extend north as far as Geraldton, Western Australia (latitude 29°S) and Narrabri, New South Wales (latitude 30°S) and south to latitude 37°S. They are found between longitudes 115°E and 150°E.

The climatic environment of the reddish chestnut soils is continental: warm-temperate and subhumid. Average annual rainfall varies from 20 to 30 inches. Winters are moderate and rather short; summers long and hot. Mean annual temperatures range from 55° to 70°F. Red-brown earths are found in the 16- to 26-inch rainfall zone of southern Australia. There is a marked winter maximum in rainfall distribution. Mean annual temperatures range from 55° to 65°F. Summers are long and hot and winters mild and moist. Higher average temperatures and a winter minimum in rainfall distribution reduce the effectiveness of the rainfall in the American soil group. The effectiveness as a leaching agent would appear to be very similar in both American and Australian soil groups.

The Australian group of red-brown earths is found on undulating to almost level plain country. The parent material consists largely of the unconsolidated products of rock weathering of colluvial and alluvial origin. The associated vegetation is savannah—open woodland with a ground flora of grasses and herbs. The corresponding American environment is the undulating grassy plain of Kansas, Oklahoma, and Texas.

The soils of California, which have developed under a Mediterranean type of climate, might have been expected to show some affinities with the red-brown earths of Australia. The presence of a range of high mountains close to the coast, however, prevents an even distribution of the rainfall. Precipitation is excessive at the higher altitudes and deficient in the intermountain areas. The soils show great variability. There is no large body of Californian soils similar to the red-brown earths of Australia. The group of noncalcareous brown (Shantung brown) soils has many points of similarity, but there is no calcium carbonate horizon. Representative soil series are the Placentia, Ramona, Vista, Holland, and Sierra (4, 5, 6, 10, 11).

#### MORPHOLOGY OF THE REDDISH CHESTNUT SOILS

The reddish chestnut soils are developed on the grassy plains from southern Kansas, through Oklahoma and Texas to the Gulf of Mexico. The climate is warm-temperate and semiarid or subhumid. The surface soils are typically dark reddish brown and friable, and the subsoils heavier and tougher, reddish brown to red in the upper part, and lighter or grayer in color and highly calcareous in the lower part. The vegetation is largely grasses, but in places there is a scattered growth of brush and small trees, and on some of the sandier areas a thick growth of small shin oak trees. These soils have relatively high inherent fertility, but the low rainfall and high rate of evaporation tend to limit crop growth. Important crops are cotton, grain sorghums, and wheat. Much of the land is used for grazing livestock (25, p. 1085).

Six subareas are described, as follows:

1. Amarillo areas of the high plains of western Texas and eastern New Mexico.
2. Duval-Webb areas of southern Texas on the Rio Grande plain section of the Coastal plain.

3. Greensburg-Pullman-Richfield areas of the high plains of southern Kansas and the Texas and Oklahoma Panhandle.

4. Miles-Vernon areas of the rolling plains section of northern and northwestern Texas, western Oklahoma, and southern Kansas.

5. St. Paul-Abilene areas of the rolling plains section of northcentral Texas and southwestern Oklahoma.

6. Zita-Pullman areas of the treeless high plains of southwestern Kansas, western Oklahoma, northwestern Texas, and northwestern New Mexico.

*Amarillo* (7, 8) areas lie in the 15-20-inch average rainfall belt. Big Spring, Howard County, Texas, has a mean annual temperature of 64.6°F. and mean precipitation of 18.4 inches. The *Amarillo* soil series combines some of the characteristics of the Australian red-brown earth and Mallee groups. The parent material appears to be of aeolian origin, and free calcium carbonate may occur in the upper horizons of the more shallow phases of the series.

*Duval Webb* (9, 15, 19, 20, 21) areas lie in the 20-30-inch rainfall zone. Le Pryor, Zavala County, Texas, has mean annual temperature of 69.4°F. and mean annual precipitation of 20.94 inches.

*Duval* fine sandy loam is described as follows:

	Depth, inches	
A	0-15	Red-brown or dark red-brown, fine sandy loam; friable and noncalcareous.
B <sub>1</sub>	15-30	Red or dark red fine sandy clay; friable and noncalcareous.
	30-40	Red-yellow or yellow-red fine sandy clay; noncalcareous, less heavy than the 15-30-inch layer.
B <sub>2</sub>	40-80	Red-yellow calcareous fine sandy clay with soft and hard lumps of CaCO <sub>3</sub> .
C	80	Mottled yellow and gray sandy clay.

*Webb* fine sandy loam is described as follows:

	Depth, inches	
A	0-10	Red-brown fine sandy loam; single-grain structure; neutral reaction.
B <sub>1</sub>	10-20	Red-brown fine sandy clay; very compact and faintly alkaline.
	20-30	Red-brown fine sandy clay; calcareous in lower part.
B <sub>2</sub>	30-54	Brown-red fine sandy clay; calcareous, containing soft lumps of CaCO <sub>3</sub> .
C	54-72	Light gray chalky fine sandy clay.

*Greensburg-Pullman-Richfield* (1, 8) areas lie in the 20-30-inch rainfall zone. *Richfield* silty clay loam is described as follows:

	Depth, inches	
A	0-4	Very dark brown silty clay loam; noncalcareous.
B <sub>1</sub>	4-8	Very dark brown clay; crumbly but not very friable; noncalcareous.
	8-16	Dark brown clay; noncalcareous.
	16-30	Brown clay; noncalcareous.
B <sub>2</sub>	30-	Brown clay; calcareous.

Profile 0-1 inches, pH 7.1; 1-8 inches, pH 7.0; 8-18 inches, pH 7.1; 18-27 inches pH 7.5; 27-48 inches, pH 8.3.

*Miles-Vernon* (1, 2, 7, 8, 12, 13, 14, 16) areas lie in the 20-30-inch rainfall zone.

	<i>Av. Tempera- ture, °F.</i>	<i>Av. Precipita- tion, inches</i>
Spur, Dickens Co., Texas	61.0	22.55
Canadian, Hemphill Co., Texas	58.1	22.97
Coleman, Coleman Co., Texas	64.7	27.79
Alva, Woods Co., Oklahoma	58.6	28.75
Norwich, Kingman Co., Kansas	57.2	29.33

Miles fine sandy loam is described as follows:

	<i>Depth, inches</i>	
A	0-10	Gray-brown fine sand; loose; noncalcareous.
B <sub>1</sub>	10-26	Red fine sandy clay; noncalcareous; heavy but crumbly.
	26-40	Yellow-red fine sandy clay; noncalcareous; more sandy than the 10-26-inch layer.
B <sub>2</sub>	40-	Calcareous layer.

Vernon very fine sandy loam occurs on undulating to steeply sloping land. It is described as follows:

	<i>Depth, inches</i>		
A	0-9	Red-brown loam; noncalcareous	} These horizons are sometimes described as calcareous.
B	9-26	Red-brown silty clay; noncalcareous	
C	26-	Shaly consolidated silty clay.	

*St. Paul-Abilene* (1, 2, 7, 8, 14) areas lie in the 20-30-inch rainfall zone. The more important soil series are Abilene, St. Paul, Roscoe, Foard, and Hollister.

Foard silty clay loam is described as follows:

	<i>Depth, inches</i>	
A	0-8	Dark brown silty clay loam; slightly laminated; noncalcareous.
B <sub>1</sub>	8-24	Very dark brown or dark gray-brown clay; noncalcareous; dense and rough.
B <sub>2</sub>	24-36	Brown or gray-brown heavy clay with CaCO <sub>3</sub> .
C	36-	Red-brown calcareous fine sandy clay.

Abilene clay loam is described as follows:

	<i>Depth, inches</i>	
A	0-8	Dark brown clay loam; friable, granular; noncalcareous.
B <sub>1</sub>	8-18	Very dark brown clay; granular; noncalcareous.
	18-30	Red-brown clay; noncalcareous; less granular than the 8-18-inch layer.
	30-42	Red clay; noncalcareous.
B <sub>2</sub>	42-	Calcareous clay.

Profile 0-4 inches, pH 7.5; 4-8 inches, pH 6.9; 8-20 inches, pH 7.4; 20-24 inches, pH 8.1; 24-48 inches, pH 8.3.

*Zita-Pullman* areas lie in the 15-22-inch rainfall belt.

Zita silty clay loam is described as follows:

	<i>Depth, inches</i>	
A	0-2	Dark brown silty clay loam; noncalcareous.
B <sub>1</sub>	2-14	Dark brown clay; noncalcareous; granular; cracks vertically to form irregular clods.
	14-30	Brown heavy clay; noncalcareous; cloddy.
B <sub>2</sub>	30-70	Brown clay; friable; calcareous; and crumbly.
C	70-	Yellow-brown clay; calcareous.

#### MORPHOLOGY OF THE RED-BROWN EARTHS

The Australian zonal group of red-brown earths is found on the hills and plains of the well-watered inland districts of the states of New South Wales, Victoria, and South Australia. It is the normally occurring soil formation found in south-eastern Australia in the 15-25-inch rainfall belt. There is a characteristic vegetation association of savannah-woodland. The climatic range is from sub-humid to semiarid, with a marked winter maximum in rainfall distribution. Under subhumid conditions the surface soil is a deep brown color with a bright red-brown B horizon, but in the semiarid range the soil is of a lighter and duller shade of brown. These soils have relatively high inherent fertility, but the comparatively low rainfall tends to limit crop growth. They are widely used for wheat growing and for stock raising, of which sheep for wool and meat production are of major importance. Certain areas in New South Wales and Victoria are included in irrigation schemes where the main crops are pastures and fruit trees.

Soil profiles of the red-brown earth type are found in Western Australia under a similar climatic environment. The physiographic environment of a recently uplifted lateritic peneplain in this region, however, has prevented the general development of soils of the red-brown earth type. The Western Australian profiles, for that reason, are omitted from the present discussion.

The zonal group of red-brown earths was first recognized and named by Prescott (18). Piper (17) later published detailed analytical data for approximately 30 soil profiles which had been selected at random throughout the South Australian zone. From a consideration of his data, Piper was able to show the range in such characteristics as mechanical analysis, calcium carbonate, reaction, nitrogen, and organic matter, hydrochloric-acid extracts, reactive manganic oxide, soluble salts, exchangeable cations, and the composition of the clay fraction. In absence of detailed field work, however, the range of characteristics shown by Piper's data must be interpreted with caution; they cannot be regarded as representing accurately the limits of variation within the group. Detailed soil surveys have been carried out at four localities within the red-brown earth zone as follows:

1. County Victoria, South Australia (24).
2. County Moira, Victoria (3).
3. Berriquin Irrigation District, New South Wales (23).
4. Wakool Irrigation District, New South Wales (22).

*County Victoria* lies in the 13-20-inch rainfall belt of South Australia. Jamestown has a mean annual precipitation of 17.7 inches and a mean annual temperature of 58°F. There is an alternate ridge and valley topography, which is paralleled by sharp local changes in climate and soils. Not all the soils are zonal, and not all zonal soils are red-brown earths. The pattern is dominated, however, by profiles of the red-brown earth type, the more important series of which are Belalie and Canowie.

Belalie loam is described as follows:

	Depth, inches		pH
A <sub>1</sub>	0-7	Brown loam, compact, noncalcareous	6.9
A <sub>2</sub>	7-14	Brown loam or clay loam	7.1
B <sub>1</sub>	14-36	Red-brown clay; small columnar structure	7.7
B <sub>2</sub>	36-48	Red-brown clay; nutty structure; slightly calcareous	8.8

Canowie loam is described as follows:

	Depth, inches		pH
A <sub>1</sub>	0-3	Brown loam; compact; noncalcareous	7.3
A <sub>2</sub>	3-5	Brown loam; massive	—
B <sub>1</sub>	5-11	Dark red-brown clay; nutty structure	8.1
B <sub>2</sub>	11-17	Red-brown clay; slightly calcareous	9.1
C	17-		

*County Moira* lies within the 15-20-inch rainfall belt of Northern Victoria. Nurmurkah has a mean annual precipitation of 17 inches, average annual temperature of 60°F., and annual evaporation (calculated) of 51 inches. The landscape consists of immense plains of old alluvium laid down by Murray River and its tributaries. The more important soil series are Moira, Cobram, Naringaningalook, Muckatah, and Katunga.

Moira loam is described as follows:

	Depth, inches		pH
A <sub>1</sub>	0-6	Brown loam; noncalcareous; mellow	6.4
A <sub>2</sub>	6-8	Light brown loam; weakly cemented	—
B <sub>1</sub>	8-27	Red-brown heavy clay; massive columns	7.4
B <sub>2</sub>	27-40	Mottled yellow-brown heavy clay; slightly calcareous	9.2

Cobram sandy loam is described as follows:

	Depth, inches		pH
A <sub>1</sub>	0-8	Brown sandy loam; structureless; noncalcareous	6.4
A <sub>2</sub>	8-18	Light brown sandy loam	7.8
B <sub>1</sub>	18-27	Red-brown sandy clay; massive	8.7
B <sub>2</sub>	27-36	Grayish brown sandy clay	9.1



Naringaningalook clay loam is described as follows:

	Depth, inches		pH
A <sub>1</sub>	0-5	Gray-brown clay loam; structureless; noncalcareous	6.5
A <sub>2</sub>	5-7	Light gray-brown sandy clay loam; "bleached layer"	—
B <sub>1</sub>	7-24	Dark gray-brown heavy clay; massive	7.4
B <sub>2</sub>	24-40	Mottled gray-brown and yellow-gray heavy clay; massive and slightly cal- careous	8.9

*Berriquin Irrigation District* lies in the southern Riverina district of New South Wales, on the opposite side of Murray River from the County Moira district of Victoria. It lies within the 15-20-inch rainfall belt. The landscape consists of immense plains of old alluvium laid down by Murray River and its tributaries. An interesting sequence can be observed in this area where the red-brown earth profiles give way to gray and brown soils of the treeless plains. The most important red-brown earth series are Cobram, Katunga, Moira, Naringaningalook, Birginbigil, Tuppal, and Mundiwa.

Mundiwa loam is described as follows:

	Depth, inches		pH
A	0-4	Brown loam; rather compact	6.5
B <sub>1</sub>	4-26	Dark red-brown heavy clay; massive	7.9
B <sub>2</sub>	26-39	Mottled yellow-brown and yellow-gray heavy clay; gypseous and calcareous	8.1

*Wakool Irrigation District* lies in the southern Riverina district of New South Wales within the 12-16-inch rainfall belt. Deniliquin has an average annual precipitation of 16 inches, average annual temperature of 62°F., and annual evaporation (calculated) of 60 inches. The landscape consists of immense plains of old alluvium. This is the extreme range of the red-brown earths, which here form an island of soil within much larger areas of gray and brown soils. The most important red-brown earth series are Wakool and Burraboi.

Wakool sandy loam is described as follows:

	Depth, inches		pH
A <sub>1</sub>	0-8	Brown fine sandy loam; structureless	6.0
A <sub>2</sub>	8-11	Light gray-brown fine sandy loam	—
B <sub>1</sub>	11-18	Brown fine sandy clay loam; friable	7.7
B <sub>2</sub>	18-24	Dark yellow-brown fine sandy clay; cal- careous	8.8

Burraboi gravelly sandy loam is described as follows:

	Depth, inches		pH
A <sub>1</sub>	0-5	Brown gravelly sandy loam; structure- less; noncalcareous	6.1
A <sub>2</sub>	5-13	Light brown gravelly sand	6.3
B	13-18	Brown gravelly sandy clay loam	7.3
C	18-	Stratified gravels	8.4

## DISCUSSION

The published Australian data for the red-brown earth group of soils have been fully drawn upon for profile descriptions. There is, however, a considerable body of analytical data that has not been reproduced here. This information is readily available in the original publications.

Only part of the available information for the American group of reddish chestnut soils, of course, has been used in this article. Very few chemical data, for instance, are included in the U. S. Department of Agriculture soil survey bulletins referred to in the bibliography. Americans who are in possession of such data will be able to carry out the comparison quantitatively.

The descriptions of the soil series from the two continental groups show, in a general way, the range of characteristics permitted within each soil group. All descriptions, for instance, emphasize the marked textural difference between A and B horizons. A further general characteristic is the absence of hardpans in these soils, although in Australia at least, farmers are accustomed to refer to the top of the B<sub>1</sub> horizon as a "claypan." It can be fairly said that all the profiles described for both great soil groups fall within the limits of the following generalized description:

The A horizon is brown in color, of medium texture, 2 to 15 inches thick, noncalcareous, of weakly acid to neutral reaction, often slightly laminated structure, and without a well-developed A<sub>2</sub> horizon.

The B<sub>1</sub> horizon is reddish brown to red in color, of clay texture but generally friable, noncalcareous and faintly alkaline, approximately 15 inches thick, and merging into the B<sub>2</sub>, where flecks of calcium carbonate appear.

The B<sub>2</sub> horizon is reddish brown to yellow-brown in color, of sandy clay texture (rather less clay than B<sub>1</sub>), with flecks and nodules of soft and hard calcium carbonate, merging gradually with the C horizon.

The C horizon is a slightly calcareous unconsolidated clay stratum.

Is this degree of uniformity between great soil groups of two continents sufficient to give them a common identity? That is the question to be answered. The author feels that existing great soil groups are not sufficiently well defined for a definite answer to be given. The author has noted, however, recent articles and discussions in the Proceedings of the Soil Science Society of America which indicate that United States soil surveyors are making a concerted effort to place all named soil series within one or other of the great soil groups. This approach, which makes use of quantitatively defined units (soil series) to define the limits of variation within the broader categories, is one that commends itself to the author. It is the approach used in this article to relate broad groups of soils in two different continents. The author awaits with interest the reaction of his American colleagues.

As a further exercise in soil classification, comparisons may be drawn between individual series. Duval fine sandy loam, Cobram sandy loam, and Wakool sandy loam, for instance, show a close parallelism, as do Webb loam and Belalie loam. A detailed discussion at this level is, however, beyond the scope of this paper. It is worth mentioning here, however, that C. G. Stephens of Adelaide

noted on a recent American field trip the close similarity between Webb loam and Waite loam (a red-brown earth series from Adelaide, South Australia).

#### SUMMARY AND CONCLUSIONS

Descriptions are presented of representative soil series belonging to the American zonal group of reddish chestnut soils and the Australian zonal group of red-brown earths. The data presented show that many characteristics are common to these two great soil groups. The author hesitates to claim a common identity for them among great soil groups of the world, however, because he feels that at the moment these categories in soil classification are not sufficiently well defined. The paper draws attention to the need for more exact standards in defining the broader units in soil classification.

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# WEATHERING AND SOIL EVOLUTION

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About 50 years ago, Dokuchaev<sup>1</sup> established that the soil is a function of climate, vegetation and other organisms, parent material, and time or age. A few years later the fifth factor of soil formation, relief, was added to the original formula. Since that time the idea that the soil is a function of these five principal factors has been universally recognized and attempts have been made to express these factors in appropriate measures and analyze the formula mathematically.

That the factors of soil formation are variables is a foregone conclusion, the logical deduction from which is the assumption of evolutionary changes of the soil with changes in its environment. This deduction had a profound influence upon the philosophy of the Russian school of soil science but has not been given sufficient attention in other countries.

The idea of the evolution of soil was expressed particularly clearly by Kossovich, who stated that soils now existing represent merely a current stage of a continuous process of their development. They could have had an entirely different character in the past and may undergo fundamental changes in the future, even "without any changes in the environment."<sup>2</sup> Hence, Kossovich was, probably, the first to adopt the idea of the autogenic evolution or "self-development of the soil independently of the environment."

Another soil scientist who contributed a great deal to the theory of soil evolution was V. R. Williams of the Timiryasev Academy of Agriculture. Williams developed the concept of a continuous, universal soil-forming process, the different stages of which are represented by the existing principal soil types. According to Williams the stages gradually replace one another in time as well as in space. It is assumed that the number of distinct stages of soil evolution is rather small, and, since the duration of each stage is limited, every given stage must reappear, in the long run, in successive evolutionary cycles. During each stage, however, the soil acquires certain permanent characteristics that cannot be obliterated during the following stages. Hence, each recurring stage begins with a condition of the soil system that is different from the condition of such a system at the beginning of the previous operation of the same stage. Thus, the cycles are not merely an endless repetition but develop in a sort of evolutionary spiral (Williams, Vilenskiy, Remesov, Kovda, and others).

A brief summary of the philosophy of the Russian school of soil science is given in the editor's introduction to a symposium on the genesis and geography of

<sup>1</sup> Dokuchaev, V. V. *On the Theory of Natural Zones*. [In Russian.] St. Petersburg. 1899.

<sup>2</sup> Kossovich, P. A. *Principles of Soil Science*, Part II, Sect. 1. [In Russian.] St. Petersburg. 1911.

soils.<sup>3</sup> According to this source, one of the major achievements of the Russian school is the development of the concept of soil formation as a succession of continuous changes of the matter which make impossible stabilization of any particular stage of the process. Having recognized the continuity of an evolutionary process, the soil scientist was forced to abandon the concept of stable soil types in a fixed equilibrium with the environment. Equipped with the new ideas, he began to study soils in historical perspective, rather than merely to analyze their morphology and composition. Naturally, he had to change also the concept of soil geography because, to him, the changes of soil in space became inseparable from their changes in time. In other words, his new soil geography acquired historical depth or a sort of the fourth dimension.

The most recent contribution to the development of the theory of soil evolution is a monograph by Rode,<sup>4</sup> who states that soil evolution is a natural consequence of soil formation. The general process of soil formation is a combination of various contributing processes, some of which are cyclic and others rectilinear or "progressive." The latter consist largely of the decomposition of primary minerals and operate continuously. Their effects are irreversible: at any time they may impart to the soil some changes in composition, which gradually accumulate and lead to eventual evolutionary changes in general character of the soil.

#### THEORY OF SOIL EVOLUTION

Fundamentally, the theory of soil evolution is based on two assumptions: one, that development of the soil is affected continuously by certain *progressive* processes; and the other, that the concurring specifically pedogenic processes do not operate steadily. Each such process begins, develops to a peak in its effect upon soil, and then dwindles to the vanishing point. It is postulated that the development of each process inevitably leads toward its own negation and eventual replacement by the other, irrespective of any changes in the environment. The development of any given process from its inception to the peak superposes itself upon the gradual decline of the other process which dominated the preceding stage of soil evolution, whereas its own decline is accompanied by the development of still other new processes. In other words, various processes operate in the soil in successive waves and every soil is affected at any given time by different processes, the effects of some of which increase in strength while those of the others undergo gradual obliteration. The character of the soil at any given time is determined by the dominant process. Besides these dominant characteristics, however, every soil possesses other characteristics, some of which gradually grow stronger while the others are vanishing. The former represent the inception of the forthcoming stage of the evolution of the soil, and the latter the evidence of the preceding stage.

The theory of autogenic evolution which is based on these assumptions is purely empirical and subject to the usual weakness inherent in such a method of

<sup>3</sup> Studies in the Genesis and Geography of Soils. Dukuchaev Soil Institute of the Academy of Science of the USSR, Moscow. 1935.

<sup>4</sup> Rode, A. A. Process of Soil Formation and the Evolution of Soils. [In Russian.] Moscow. 1947.

reasoning. The very idea about the autogenic evolutionary changes of the soil contradicts the fundamental principle that the soil is a function of certain natural conditions. No independent change is compatible with a functional relationship. A function can and must change only in connection with changes in the factors of which it is a function. Hence, either the soil is not a function of the factors of its formation, outside of which it simply does not exist, or its autogenic evolution is impossible.

There is nothing sacrosanct, indeed, in Dokuchaev's postulate that the soil is a function of climate, vegetation, and various other factors. It is equally well recognized that soil, climate, vegetation, parent material, and various other elements are thoroughly integrated in certain geographical complexes. Each component of such complexes may be referred to either as a function or as a factor, depending on the point of view. As regards soil science, the soil is a function of, say, climate and vegetation. As regards plant ecology, plant association is a function of the soil and climate, and therefore an ecologist may consider soil as a factor of plant ecology. It may be somewhat more difficult to consider the climate as a function, but in soil genetics we refer not so much to the climate of the air as to the soil climate, and the soil climate is a function of the medium in which it operates, that is, the soil, and the climate of the air.

Thus, the concept of the soil as an integrated element of the broader geographical systems in no way conflicts with the specific definition of the soil as a function of other elements of such a system. In considering the evolution of soil, one is considering an evolution of the function, and this excludes any possibility of independent or autogenic changes.

Dependence of changes in function upon the changes in factors does not indicate that the latter must antedate the former. In a thoroughly integrated system, changes inevitably arise and develop simultaneously. No changes in function are possible without changes in factors, and no changes in factors can fail to affect the character of the function. It is the fact of synchronism of changes in factors and functions which may be the source of some confusion between causes and consequences.

The concept of the inevitability of continuous or progressive changes of the soil, whether along an evolutionary spiral or otherwise, is based largely on the assumption that certain irreversible processes continuously affect soil formation. As has already been pointed out, these processes consist especially, if not entirely, of the decomposition of primary minerals which are unstable in the thermodynamic field of pedosphere. More commonly these processes are conceived as an essential part of weathering. Their irreversibility refers to the fact that resynthesis of the original minerals from the products of their decomposition in the soil, which is subject to weathering, is impossible. Hence, it is assumed that primary minerals lost through weathering are not replenished, and the content of such minerals in the soil gradually decreases, whereas the products of their decomposition, according to Polynov<sup>5</sup> and Rode, "are subject to progressive transformation." According to Polynov, "the transformation of the mineral com-

<sup>5</sup> Polynov, B. B. Time as a factor of soil formation. [In Russian.] *Trans. Dokuchaev Soil Com.* No. 3-4:156-171. St. Petersburg. 1916.

pounds of the soil represents that very factor which introduces a progressive element into soil formation and gives a forward movement to the soil cycle."

A rather theoretical assumption that decomposition of unstable primary minerals is an endless progressive process is entirely untenable. It refers, obviously, to a given mass of a fixed material which, presumably, is subject to certain changes due to the breaking down of primary minerals and leaching but which otherwise remains stable. Such a condition, however, does not exist. If it were real, then the earth, or at least a certain part of it, would be wrapped in a *lifeless mantle thoroughly deprived of the unstable minerals, composed entirely of those most resistant to any further changes, and, hence, essentially static*. The earth is old enough for any steady rectilinear or progressive process to reach its culmination somewhere if its effects were not eradicated just as steadily by some concurrent other process. No information of such a mantle or even a tendency for such a formation has been found anywhere.

Referring to a particular case of the leaching of calcium, Rode states that eventual total loss of this element must lead to inevitable death of the soil and the entire organic world. Obviously, calcium is not an exception; what holds for calcium must hold for any other element too. As a matter of fact, however, nothing of this sort ever happened anywhere on earth. Irrespective of the geological age, the petrographic composition of various regoliths does not vary much beyond the differences which are due to differences in composition of the initial bedrocks.

The only possible conclusion from these facts is that the so-called "progressive" process of decomposition of unstable minerals is not progressive in the sense ascribed to it and that its effect is subject to a steady obliteration by some concurrent process. Precise data on the concurrent processes which might check the cumulation of the effects of weathering and maintain a steady state of the system that is subject to it are meager, indeed, and the concept of such processes and of their role is based largely on inferences such as the following: If resynthesis of the broken-down primary minerals is impossible under conditions in which these minerals undergo decomposition, and if the leached compounds do not return to the material from which they were removed, then one may infer that the steady state of the material which is affected by these processes can be maintained only by the steady removal of the worn-out epidermis of the crust of weathering and a simultaneous sinking of the horizon in which the decomposition and leaching are taking place.

A sinking of the horizon of weathering should accompany the removal of the senile material from the surface, because such a removal allows a deeper penetration of the parent material by the factors of weathering. Perhaps such a skinning of the epidermis and an increase in depth of weathering amount to mere films at a given time interval; nevertheless, they must steadily balance each other and be adjusted to the local conditions. Collectively these processes lead to a steady renovation of the material, without which sooner or later all unstable minerals in this material would be broken down.



## PARENT MATERIAL

Consideration of these processes touches on the concept of the soil parent material. No definition of any soil is complete without reference to its parent material. The parent material, one of the essential factors of soil formation, always is regarded as something different from the soil which might develop from such a material. Usually it is defined as the material that is not modified or affected by any pedogenic process or as a fresh regolith.

Every regolith, whether residual or transported, is not a *deus ex machina*. It results from the operation of a certain process, *the process of parent material formation*, which is nothing more than what is commonly referred to as weathering, including breaking down of bedrocks, decomposition of the primary minerals, and shifting, sorting, and redeposition of the ensuing debris. As long as we differentiate between the soil and its parent material and recognize the latter as an essential individual factor of soil formation, we necessarily must differentiate between the respective processes of soil and parent material formation. In other words, we have to differentiate between weathering and soil formation, notwithstanding the difficulty of such a differentiation. The difficulty is largely due to the fact that both processes operate simultaneously in the same medium and hence continuously overlap and affect each other.

Being fully aware of an unavoidable arbitrariness of any differentiation between the intimately interrelated processes, the author is inclined to conceive the entire pedogenic process as cyclic and distinct from the rectilinear weathering that leads to development of the soil parent material.

The rectilinearity of weathering is not absolute, indeed. Weathering is a part of the much broader geochemical cycles. The difference between the pedogenic and geochemical cycles is first of all in the time scale. Consider, for example, the pedogenic and geochemical cycles of calcium.

Suppose that the pedogenic cycle of calcium begins from its release in a free oxide state. It makes no difference whether it was liberated by decomposition of some primary mineral or of organic residue, or was introduced by the farmer in form of lime. A part of it, probably, will be leached, another part fixed in some insoluble salt, and still another retained in an exchangeable form. Sooner or later, part of the exchangeable calcium will be taken up by the roots and transferred into the tissue of the plant, then returned to the soil in organic residue and ultimately released again. The whole cycle may take a year or several years.

The geochemical cycle of calcium may include its release by weathering, leaching, a long trek to the ocean, segregation by marine fauna, sedimentation in the form of limestone, uplift of the sea bottom, and other liberation by weathering. It may take many millions of years.

Generally the parent material is conceived as something rather static that has been deposited or formed in place and remained inert until revitalization by the soil development. Weathering, however, goes on whether the new pedogenic processes are superimposed upon it or not. Theoretically, it would come to an eventual standstill if its destructive—as regards the unstable minerals—function

were not accompanied by the steady renovation of the medium in which it takes place.

It is probable that in the early stages of weathering the rate of renovation of the source material is very low in comparison with the rate of decomposition of this material. The weathering should advance and the ensuing regolith should acquire a certain character. The rate of renovation of the initial material presumably rises with the advancement of weathering and in time becomes sufficient for balancing the decomposition. This stage may be called the stage of *stabilization of weathering*. The regolith reaches a steady state in such a stage and may be referred to as a *mature parent material of the soil*. This material is the product of a progressive weathering, the progressiveness of which, however, refers essentially to a gradual gnawing deeper into the underlying rocks, whether solid or loose, and simultaneous casting away of the worn-out epidermis, rather than continuous changes in composition of a fixed material. Hence, the author cannot agree with the assumption that the content of primary minerals in the soil is not replenished, whereas the products of their decomposition, according to Polynov and Rode, undergo progressive transformation. The primary minerals in the soil are replaceable through a steady renovation of the material, and in the long run their content, probably, does not change, notwithstanding a steady decomposition, whereas the products of their decomposition do not undergo an endless "progressive" transformation but simply are removed by erosion, deflation, leaching, and recrystallization, all of which are essential functions of weathering.

Continuity of weathering which is conditioned by removal of the senile products and renovation of the material indicates that the parent material of the soil is by no means static. Probably, it is its own dynamism that makes possible development of the more dynamic soil from it and, on the soil, of the still more dynamic plant and animal kingdoms.

Having recognized the parent material of the soil as an individual entity, one must go a step farther and differentiate between this material and the rock. Usually it is assumed that the parent material, unmodified by soil formation, is more or less uniform in composition to the undefined depth. This, perhaps, is another theoretical misconception. The parent material is a function of weathering, and weathering affects the rocks only to the depth that can be reached by its forces. The effects of weathering are not uniform throughout the layer in which it takes place; hence, the parent material itself must acquire a certain profile composed of different horizons—horizons of weathering. The uppermost of these horizons may coincide with or be further differentiated into the more specific soil horizons, whereas the lower ones, especially those in the C zone, may be little, if at all, affected by the pedogenic activity. The character of each horizon, whether that of the soil or that of the parent material, depends upon a specific character of the process which operates in this layer and *the position of any horizon in the profile is determined by the depth which can be reached by the factors that keep this process in operation.*

The question may be raised whether sedimentation of the removed material would not allow weathering to advance beyond the stage of maturity at the pre-

ceding phase and thus—after a series of redepositions—render the sediments progressively more sterile. Undoubtedly, it would. The eroded material undergoes mechanical and petrographic sorting and may come to temporary rest many times before being carried to the sea. Whenever it settles, whether for millenia or for just a few days, it is subject to further weathering, which, in fact, does not stop even when the material is in motion, and if time and the rate of accumulation permit, may come to a new steady state corresponding to the new set of conditions.

#### EVOLUTION OF NONCUMULATIVE SOIL

The steady state of the parent material presupposes a steady skinning of the surface accompanied by a gradual sinking of the horizon of weathering. If such a material is modified into a soil, this soil, if it exists long enough, should gradually lose the material from which its original A horizon was formed, then the material of the original B horizon, then the C material, whereas the A horizon of the soil, passing through the subsequent stages, should develop from the material which was the seat of the B during the preceding stage and still earlier in the C condition. In other words, *the A horizon of every mature, noncumulative soil develops from the material that previously passed through the stage of the B horizon, rather than directly from the C material.*

It should not be interpreted that development of the A horizon follows development of the B and has no influence upon the character of the latter. The soil horizons develop simultaneously. Skinning of the A horizon is accompanied by encroachment of this horizon upon the B and sinking of the B deeper into the C horizon. In this process the effects of each horizon upon the others are gradually transferred to the successively lower levels without changes in the general character of the whole profile.

In this connection, a note about so-called "old soils" may be in order. The soil may be a hundred thousand, a million, or several millions of years old. This does not mean, however, that the A horizon of the present soil consists of the material that was in the A horizon, say, a million years ago. The material of the present A horizon, probably was a solid rock at that time. The material of the original A horizon as well as that of the other horizons could have been stripped away. Together with it, naturally, had to go the various "permanent" characteristics which might have been acquired by the soil during the preceding stages of evolution. Hence, the slow evolutionary changes, except for the most recent ones, are not superposed upon the ancient soil profiles, but gradually, so to say, slide down from them upon the fresher material which was not affected by pedogenesis during the preceding stages of evolution. By the way, this may be one of the causes of an extreme meagerness of paleopedological data.

We do not know yet how much time a complete renovation of the soil body might require: in some instances, perhaps, a hundred thousand years; in others, ten thousand; and in still others, probably, not more than a century. In any case, it may be expected that a soil which has existed since, say, the last Pleistocene glaciation still preserves some records of its evolution. Under favorable

conditions outside the glaciated area, such records may extend two or even three times as far into the past, but hardly more anywhere on the earth.

#### PEDOGENIC CYCLES

The process of renovation of the parent material described above is not universal. There is no geological erosion or deflation that is not accompanied by sedimentation, and sedimentation must build up the soils and bury the old horizons instead of skinning and pushing them down. The effects of this process upon the formation and evolution of soils cannot be fully understood without a closer examination of the essence of the cyclic processes of soil formation proper.

It is assumed that the cyclicality of the processes of soil formation depends upon the uneven inflow of the radiant energy which keeps these processes in a steady motion. Accordingly, references are made to diurnal, annual, and various other cycles.

The author conceives the pedogenic cycles in a somewhat different aspect. Diurnal or annual changes in temperature or moisture represent a succession of waves or pulsation rather than cycles. By *cyclic processes*, the author refers to the chain transformation of the matter and energy in the course of which the matter and energy periodically reappear in the same form. Hence, one may consider pedogenic cycles of heat, water, organic matter, carbon, nitrogen, calcium, phosphorus, sulfur, iron, in fact, any of the elements.

A *pedogenic cycle of heat* does not refer merely to the diurnal or annual runs of temperature in the soil. It refers to the heat that may be absorbed by or generated in the soil, to the calories that are required by various endothermic reactions which take place in the soil, to the amount of heat that is released by the reverse exothermic reactions, to the transmission of heat from one horizon to the other and its radiation.

In a similar way, the *cycle of water* does not consist merely of alternating saturation and desiccation of the soil, but refers to the water that enters the soil, is used for building up organic matter or for hydration and hydrolysis, is released by the reverse processes, and is removed by transpiration, evaporation, and percolation. Water which enters the soil, whether vadose or juvenile, is only a source of water that takes a part in the pedogenic cycles.

By way of illustration of the general mechanism of the pedogenic cycles, let us consider for a moment the cycles of organic matter. These cycles vary in character. Cycles of organic matter under annual herbaceous vegetation are different from those under forest, shrubbery, or mosses. The cycle under shrubs in tundra differs from that in the desert, and the cycles under grass in savanna differ from those in the steppe or mountain meadow. The cycle of organic matter in the desert may last less than a year, whereas in the steppe it may extend over many years.

Suppose that the cycle of organic matter under annual grasses begins from the deposition of fresh organic residue. Similar depositions are made regularly each fall, and the green matter for them is being built regularly each preceding spring and summer. A new cycle begins with each deposition of residue, but the pre-

ceding one does not end at the beginning of the new. Each cycle develops through a long chain of processes of decomposition of debris, formation of humus, its mineralization, liberation of elements, and finally their resynthesis by the new generation of grasses. Some compounds in organic residue may decompose within a few months, maybe days; some others may take many years. Various intermediate substances are formed and decomposed. The general cycle includes all these phases and extends over many years.

Hence, each year the beginning of a new cycle superposes itself upon the more advanced stages of all preceding cycles that have not yet reached final stages. Consequently, the soil organic matter in any year consists of various materials which represent all stages of the long cycle from the initial to the last. Because of this, the general composition of the soil organic matter does not change from year to year, and such a steady state conceals the cyclicality of its formation.

In speaking of pedogenic cycles, however, we do not refer to any particular atoms. It is possible that the time is not far away when we shall be able to mark individual atoms, like some of those that are now being marked by radioactivity, and trace their courses in pedogenic cycles. Then, perhaps, we shall learn that they do not migrate by cycles. The pedogenic courses of individual atoms, probably, are more or less parabolic rather than cyclic. These atoms enter the process, proceed through certain stages of it and leave it, while the other atoms take their place and pass through the following stages of the process. In considering pedogenic cycles, we refer to certain amounts of matter or energy rather than to any particular atoms or quanta. It makes no difference whatever whether any of the atoms pass through all phases of the cycle or take part only in a few of them.

All cyclic processes of soil formation are kept in motion by the living matter which controls migration of the elements and energy that are involved in these processes. This is the principal determining characteristic of all strictly pedogenic processes. The dynamics of weathering depend upon the climate; the dynamics of soil formation, upon the organic word.

#### EVOLUTION OF CUMULATIVE SOIL

Deposition of sediments on the surface of the soil buries previously formed soil horizons. Buried soils or what are believed to be buried soils have been found in many places. Their burial, however, is a rather special case which presupposes that sedimentation was interrupted for a time sufficient for the formation of a fairly well developed soil, and then, rather suddenly, rejuvenated to cover this soil with a mantle that was thick enough for its fixation.

It must be borne in mind that being a function of the factors of its formation, a dynamic soil cannot exist as such outside the conditions under which it has been formed. Burial fundamentally changes these conditions, and the soil inevitably undergoes readjustment to the new conditions. To begin with, burial deprives the soil of its principal source of energy, vegetation. Hence, all cyclic processes come to a standstill, and the elements which took part in these processes lose protection against leaching and other forces that tend to bring the old soil to the

condition of a steady state of the parent material at a given depth. This leads to a gradual but inevitable obliteration of the specific characteristics of the old soil. In other words, *soils themselves carry means for self-destruction after isolation from the environment in which they were formed*. Presumably, no complete profile of a buried soil can be preserved unless it is rapidly petrified or fixed in some other way. Not a single case of such a fixation and no evidence of its possibility have been discovered yet.

Usually, only a few characteristics of the old soil escape obliteration after burial. Most of these characteristics represent the effects of differential decomposition of primary minerals, oxidation of various products, and formation of the secondary clay minerals, all of which are largely the results of weathering.

Relics of this kind have little paleopedogenic value. There are a great many different soils but only a few different types of weathering. Hence essentially the same primary minerals decompose in the same way and the same clay minerals are formed in many different soils. All in all, these paleopedogenic bones may indicate that once upon a time a given stratigraphic horizon has been an old erosion surface and affected by weathering but hardly much more. Certainly, they do not give any reliable information as to the character of the ancient soil.

More common than spontaneous burial is the gradual up-building of the cumulative soil by slow but steady sedimentation. It may be a mere film or a few millimeters a year that gradually builds up deposits of very considerable thickness. The rate of sedimentation may be still too high for any pedogenic process to cope with it. In such cases there is no differentiation of soil horizons, and the process consists largely of building up stratified but pedogenically unmodified deposits such as the sediments of enormous alluvial fans in the desert. If, however, the rate of sedimentation is sufficiently low and the soil-forming processes are sufficiently effective, then each new film of sediments is modified and becomes an essential part of the A horizon of the soil.

The steady upbuilding of the soil does not lead to the formation of the abnormally thick A horizon. As has been pointed out, each soil horizon develops at a certain depth, at which its parent material is continuously affected by some specific process that is peculiar to such a horizon. As soon as this process ceases to operate in any part of the horizon, this part loses its individual characteristics and, figuratively, dies off, becoming subject to remaking into a different horizon. Hence, upbuilding of the soil is accompanied by a simultaneous lifting of all soil horizons.

Obviously, this is a complete reversal of the process of evolution of the non-cumulative soil described above. *The A horizon of the cumulative soil develops from the fresh assorted sediments that settle on its surface rather than from the material that previously passed through the stage of the B horizon, whereas the B horizon follows the A and develops from the sediments that passed through the stage of the A.*

This is a very important difference in the mode of development of the cumulative and noncumulative soils. In many instances this difference is not given proper attention. This leads to serious confusion in designating various soil

horizons and in interpreting their origin and peculiar characteristics. Sometimes the confusion is so great that the authors are unable to recognize the A and B horizons and refer to the first, second, third, and so on horizons without any attempt to correlate them with the standard A or B.

Cumulative soils, probably, are just as common as noncumulative. As one moves down a slope, steep or gentle, even in country with little relief, one crosses in one place or another the boundary between noncumulative and cumulative soils. Each of these soils has its own A and B horizons, but these horizons of the cumulative soil differ from the corresponding horizons of the noncumulative soil in almost every respect, especially in origin and composition.

Thus gradual upbuilding by steady sedimentation, like spontaneous burial, results in changes of the conditions of the material from which the earlier A and B horizons were formed, and these changes necessitate obliteration of the specific characteristics of these horizons. Again, some petrographic peculiarities of a rather limited paleopedogenic value might escape obliteration, but not the characteristics which are essential for analysis of the course of soil evolution.

Still more common than upbuilding by sedimentation is continuous shifting and redeposition of the material of the A horizon without any true accumulation. Usually this material is moved a short distance at a time and spread upon the surface from which about the same amount of similar material has been removed by the same agent, wind or runoff, just before its settlement. So common is this process that it is almost taken for granted that the A horizon of most soils is subject to such mechanical disturbances and its residual character hardly ever can be ascertained. Naturally, these disturbances preclude the cumulative development of any "permanent" characteristics of the soil.

#### SUMMARY AND CONCLUSION

Whether the soils are a function of the environment in which they develop or a component of thoroughly integrated geographical systems, they do not remain constant indefinitely but change with changes in the environment. Of the elements of the environment, climate, drainage, and vegetation are subject to the most significant changes, and in all likelihood these changes constitute the principal factor of the evolution of soils. Evolutional changes are not steady. In stable environment, the soils as well as their parent material reach a steady state and remain in such a condition as long as the environment remains stable. Whether such a steady state is maintained for only a short time or can persist for millenia, we have no information.

Analysis of the principal forms of the mechanism of soil formation shows little if any possibility for preservation in soils themselves of any feature which might have been acquired by them during the past stages of their evolution and a rather limited probability that much might be learned about soil evolution from occasional paleopedologic discoveries. Evolutional changes of soils consist not only of development of new characteristics but also of obliteration of previously acquired characteristics. An assumption that certain soil characteristics are per-

manent appears rather untenable because such characteristics could exist only in permanently fixed material, a condition which does not exist in nature.

Only the records of some evolutionary changes which occurred during the latest geological periods can be expected to be preserved. This refers especially to the changes in soils during the Pleistocene and post-Pleistocene epochs. Even these records are not likely to be very clear or sufficient for a complete analysis of the course of soil evolution, to say nothing of the evolutionary cycles or spiral, the very concepts of which are purely dialectic.



# TRANSFORMATION OF NITROGEN IN RICE SOIL

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Investigations on changes of nitrogen in rice and other moist soils (1, 2, 3, 4, 7, 8, 9, 10, 11) have been concerned primarily with nitrate and ammonia, and only during the period when the soils are waterlogged. No attempt appears to have been made to study the changes throughout the entire year or to consider other forms of nitrogen.

The object of the present investigation was to study the changes in different forms of nitrogen, both organic and inorganic, in rice field soils at different seasons of the year. It was hoped that the information thus obtained would be useful, first, in understanding the effect of varying seasonal conditions on nitrogen transformation in rice soil, and, second, in ascertaining the possible role played by different forms of nitrogen compounds in the nutrition of rice.

## EXPERIMENTAL PLOTS

Two unmanured plots (Khoskhana Bye and East Ravine) of the Government Agricultural Farm at Dacca were selected for the investigation. They are a furlong apart; both are low lying and have been under rice cultivation for a long time. Khoskhana Bye remains waterlogged for a longer period than East Ravine because water flows into the plot from a near-by tank after heavy rains. Rice is the only crop grown on these lands. During the fallow season, a sparse growth of grass appears; this is not removed but is mixed with the soil at the time of puddling.

In 1944-45, when these studies were made, the soils in both plots were brought to waterlogged conditions in June, and seedlings were transplanted a few days later. From June to October the soils remained completely under water, and after the supernatant water had disappeared in November, they began to dry. The crop on East Ravine was harvested in December and that on Khoskhana Bye a month later. After harvest and until the following June the soils remained fallow and dry.

## COLLECTION OF SAMPLES

Soil samples were taken about the middle of each month. A few borings (0-6-inch) were collected at random from different parts of the plot and were mixed to make a composite sample. The samples taken during the waterlogging period were too muddy to be sieved and had to be mixed by hand. Though this technique was quite satisfactory during the later stages of waterlogging, it sometimes presented difficulties during the earlier stage when samples were not uniformly muddy but were mixtures of mud from the upper layer and

<sup>1</sup> The author is grateful to P. K. De for suggesting the problem and for his criticisms during the progress of the work, and to M. Sulaiman for his valuable help.

of hard lumps of soil from the bottom layer not yet reached by water from the surface.

As soon as samples were ready, within an hour of their collection, a portion of each was taken for estimation of moisture, ammonia, and nitrate. The remainder was spread in a thin layer over a tray and allowed to air-dry.

#### METHODS OF ANALYSIS

##### *Total nitrogen*

Total nitrogen was determined by the routine Kjeldhal method on duplicate 15-gm. portions of air-dry soil.

##### *Ammonia nitrogen*

Duplicate 100-gm. portions of fresh soils were leached with 500 ml. of  $N$  KCl solution. A known volume of the leachate was used for total nitrogen determination, and the remainder was distilled with 2 gm. of ignited  $MgO$ , the ammonia evolved being absorbed in  $0.02\ N$   $H_2SO_4$  and estimated by back titration with  $0.02\ N$   $NaOH$ , methyl red being used as indicator.

##### *Nitrate nitrogen*

The  $MgO$  residue, after ammonia determination, was diluted with water and again distilled with the addition of 2 gm. of powdered Devarda's alloy. Ammonia, which is formed by the reduction of nitrate, was estimated as before. Nitrate was estimated only when the KCl extract gave a positive test with diphenylamine reagent.

##### *Soluble organic nitrogen*

From the total nitrogen content of KCl extract, the sum of ammonia and nitrate nitrogen was deducted. The difference represented the soluble organic nitrogen.

##### *Hydrolyzable nitrogen*

The residual soil, after ammonia determination, was dried in sun and then thoroughly powdered. A 100-gm. portion of this soil was heated under reflux in a water bath for 3 hours with 400 ml. of 5 per cent  $HCl$ . After cooling, the contents were filtered, washed several times with distilled water, and the filtrate was slowly evaporated over a water bath almost to dryness. The residue was dissolved in water, treated with excess of  $MgO$ , and then distilled. The ammonia evolved was absorbed in  $0.1\ N$   $H_2SO_4$  and estimated by back titration, the value representing the hydrolyzable nitrogen.

##### *Alkali-soluble nitrogen*

The residual soil after treatment with 5 per cent  $HCl$  was dried in sun, finely powdered, and a 90-gm. portion was extracted by heating with 900 ml. of  $0.5\ N$  caustic soda solution at  $45^\circ C$ . for 3 hours. After 24 hours, the clear supernatant liquid was carefully syphoned off, and a portion was analyzed for total nitrogen.

*Humic and nonhumic nitrogen*

A 500-ml. portion of the alkali extract was acidified with 30 ml. of concentrated HCl. Humic nitrogen separated as a brown flocculent precipitate, and non-humic nitrogen remained in solution. After the precipitate had settled and the supernatant liquid had become almost clear, the solution was filtered. Nitrogen content of the filtrate was determined as usual (nonhumic N), and this was subtracted from the total nitrogen content of the alkali extract to get the value for humic nitrogen.

TABLE 1

*Changes in moisture and total nitrogen contents of Khoskhana Bye and East Ravine soils*

DATE OF SAMPLING	MOISTURE		TOTAL N PER 100 GM. DRY SOIL	
	K*	E*	K	E
	%	%	mgm.	mgm.
Sept. 15, 1944.....	40.0	39.0	125.3	117.0
Oct. 17, 1944.....	42.6	40.3	126.3	117.3
Nov. 16, 1944.....	32.6	28.0	127.2	124.4
Dec. 18, 1944.....	28.5	11.2	124.1	123.0
Jan. 16, 1945†.....	24.8	15.2	124.7	120.1
Feb. 16, 1945.....	23.6	15.2	125.2	119.8
Mar. 16, 1945.....	19.4	6.9	125.5	120.1
Apr. 16, 1945†.....	23.7	22.1	125.1	120.2
May 16, 1945.....	20.0	17.1	126.0	119.5
June 18, 1945.....	40.0	34.7	125.8	119.7
July 17, 1945.....	36.6	35.4	124.9	120.2
Aug. 18, 1945.....	39.4	37.9	126.0	120.8

\* In this and following tables, K indicates Khoskhana Bye, and E East Ravine plot.

† A heavy rain fell on January 6 and again on April 12, 13, and 14.

*Nitrogen in the neutralization precipitate*

The filtrate obtained after separation of humic nitrogen was neutralized to pH 4.8 with NaOH. The precipitate formed was filtered after 24 hours, washed with water, and then analyzed for total nitrogen. This fraction of the organic nitrogen of soil has been called the *neutralization precipitate* by Hobson and Page (6) and the  $\beta$ -fraction by Waksman (12).

*Amide nitrogen*

A known volume of the filtrate from neutralization precipitate was treated with HCl to a concentration of 5 per cent and then boiled for 3 hours under reflux. The ammonia formed was estimated by the usual method and represented the amide nitrogen.

## RESULTS

The data in table 1 show that the total nitrogen content of the Khoskhana Bye soil remained at a more or less constant level throughout the year. In the

East Ravine soil, although the figures for September through December are somewhat erratic, the others show but few differences.

Table 2 shows that the ammonia contents of the soils remained at a relatively high level during July and August, that is, soon after waterlogging. But in September<sup>2</sup> the ammonia content fell rapidly, presumably as a result of assimilation of this nutrient by the growing plant, which by that time had reached the stage of active vegetative growth. Thereafter, it remained at a low level; in fact, 2 months after harvest it completely disappeared from East Ravine and was present only in trace in Khoskhana Byde. This loss of ammonia was obviously not due to its conversion to nitrate, which was still absent from the soil; it was probably due to the effect of straw, a portion of which is usually left in the soil at

TABLE 2

*Changes in ammonia, nitrate, soluble organic, and hydrolyzable nitrogen contents of Khoskhana Byde and East Ravine soils*

DATE OF SAMPLING	NH <sub>4</sub> - N		NO <sub>3</sub> - N		SOLUBLE ORGANIC N		HYDROLYZABLE N	
	K	E	K	E	K	E	K	E
	p.p.m.	p.p.m.	p.p.m.	p.p.m.	p.p.m.	p.p.m.	p.p.m.	p.p.m.
Sept. 15, 1944.....	3.6	1.3	0	0	12.8	8.4	12	39
Oct. 17, 1944.....	6.4	6.4	0	0	8.1	8.3	78	136
Nov. 16, 1944*.....	5.0	5.4	0	0	11.3	10.2	130	132
Dec. 18, 1944*.....	2.6	0	0	0	11.8	9.7	135	116
Jan. 16, 1945.....	0.4	0	0	0	11.6	9.1	84	66
Feb. 16, 1945.....	1.6	4.6	6.6	5.8	1.5	—	84	73
Mar. 16, 1945.....	2.5	2.3	5.7	0	2.9	5.6	101	103
Apr. 16, 1945.....	9.0	4.3	7.7	1.3	1.2	11.5	129	108
May 16, 1945.....	7.0	2.7	15.8	0.4	0	11.5	66	62
June 18, 1945.....	6.8	7.2	1.2	1.7	6.7	4.4	70	69
July 17, 1945.....	11.0	12.5	0	0	24.4	22.1	28	45
Aug. 18, 1945.....	12.9	20.3	0	0	18.1	20.5	25	45

\* Crop harvested in East Ravine after November 16, and that in Khoskhana Byde after December 18.

harvest. Straw is a material of wide C - N ratio, supplying an excess of energy material over the nitrogen made available from it. Consequently, when undecomposed straw is present in soil, the microorganisms, utilizing the excess energy material supplied, assimilate the available nitrogen compounds of soil.

There was no nitrate in any of the soils from July to January. In February, nitrate appeared in both plots, but whereas it rose from 6.6 p.p.m. in February to 15.8 p.p.m. in May in Khoskhana Byde, it was present in East Ravine only in trace, except on one occasion during the same period, despite the fact that the moisture content (15.2 per cent) of the latter was more favorable for nitrification than was that of the former (23.6 per cent).

<sup>2</sup> The results for July and August were obtained in 1945 and those for September in 1944. Thus, they are not continuous for the same season and are not strictly comparable. But the seasonal and cropping conditions of these 2 years were so similar that the figures may be assumed to represent the changes in consecutive months of the same year.

The changes in soluble organic nitrogen followed a course somewhat similar to that of ammonia, particularly during the waterlogging period. The amount was maximum in July, and although still high in August, it fell considerably in September. Thereafter and until a month after harvest, it remained at a rather constant level. But in subsequent months, Khoskhana Byde and East Ravine behaved differently: in the former the soluble nitrogen virtually disappeared, but in the latter it remained almost at the same level as in the previous months.

Hydrolyzable nitrogen was present in much larger amounts than any of the above three forms. Some erratic fluctuations occurred, which could not be correlated with any of the external factors. The results, on the whole, showed that hydrolyzable nitrogen was present in soil in large amounts at all seasons. It is difficult to say what is the chemical nature of the compounds included in

TABLE 3

*Changes in different forms of nitrogen in alkali extracts from Khoskhana Byde soil*  
N in milligrams per 90 gm. of acid-treated soil

DATE OF SAMPLING	TOTAL N	NONHUMIC N	HUMIC N	NONHUMIC HUMIC	NEUTRALI- ZATION N	AMIDE N
Sept. 16, 1944.....	35.28	25.43	9.85	2.6	5.04	5.2
Oct. 17, 1944.....	36.54	26.74	9.8	2.7	4.38	5.7
Nov. 16, 1944.....	31.5	21.4	10.1	2.13	5.35	4.5
Dec. 18, 1944.....	30.24	20.03	10.21	1.96	4.93	6.2
Jan. 16, 1945.....	28.97	21.38	7.59	2.82	4.68	4.2
Feb. 16, 1945.....	26.45	18.72	7.1	2.4	4.94	4.7
Mar. 16, 1945.....	27.71	20.05	7.66	2.61	4.81	4.4
Apr. 16, 1945.....	28.97	20.95	8.02	2.61	4.5	5.8
May 16, 1945.....	30.24	23.03	8.21	2.7	4.7	6.1
June 18, 1945.....	28.97	21.4	7.57	2.8	5.1	6.2
July 17, 1945.....	27.71	20.03	7.68	2.6	4.9	5.7
Aug. 18, 1945.....	30.24	22.03	8.21	2.7	4.9	5.3

this fraction. Under the very mild treatment employed—heating on a water bath with 5 per cent HCl—, only very simple substances like urea or compounds that are chemically allied to ammonia will probably undergo hydrolysis. Whatever may be the nature of these compounds, however, the results clearly show that a considerable part of the nitrogen in rice soil is present in forms that are readily hydrolyzed to ammonia.

Although certain minor discrepancies are apparent, which are to be expected in an experiment like this, there were no marked fluctuations of any of the forms of nitrogen at any time. Alkali-soluble nitrogen and nonhumic nitrogen (tables 3 and 4) showed a tendency to increase during the cropping period, but in the other months of the year they remained more or less at a stationary level. The increase observed, however, was never so high as to indicate a change of any importance. The values for neutralization precipitates and for amide nitrogen remained virtually constant throughout the year. The amide nitrogen in this fraction was obviously different from the hydrolyzable nitrogen in table 2, be-

cause the latter was obtained by direct acid treatment of the soil, whereas the former came into solution only after the humic-clay gel had been dissolved out by the alkali.

The results, on the whole, show that the different conditions that exist in a rice field have little influence on the organic makeup of the soil.

TABLE 4  
*Changes in different forms of nitrogen in alkali extracts from East Ravine soil*  
N in milligrams per 90 gm. of acid-treated soil

DATE OF SAMPLING	TOTAL N	NONHUMIC N	HUMIC N	NONHUMIC HUMIC	NEUTRALI- ZATION N	AMIDE N
Sept. 15, 1944.....	35.28	25.7	9.6	2.7	5.1	3.5
Oct. 17, 1944.....	31.5	22.91	8.59	2.7	4.79	4.2
Nov. 16, 1944.....	30.24	22.05	9.19	2.7	5.25	5.4
Dec. 18, 1944.....	30.24	20.03	10.21	1.96	4.78	4.9
Jan. 16, 1945.....	28.97	21.36	7.61	2.8	4.67	4.0
Feb. 16, 1945.....	27.71	20.05	7.66	2.62	5.1	5.0
Mar. 16, 1945.....	26.45	18.68	7.77	2.4	4.74	5.0
Apr. 16, 1945.....	27.71	20.56	7.15	2.86	4.46	5.8
May 16, 1945.....	28.97	21.37	7.6	2.8	4.7	5.6
June 18, 1945.....	27.71	20.05	7.66	2.61	4.93	4.8
July 17, 1945.....	31.5	22.7	8.8	2.58	4.81	6.0
Aug. 18, 1945.....	28.97	20.95	8.02	2.61	4.5	5.4

#### SUMMARY

Soil samples were collected at monthly intervals from two plots (Khoskhana Bye and East Ravine) of the Government Farm at Dacca and were analyzed for different forms of nitrogen.

Total nitrogen content of the soil remained virtually constant throughout the year.

There was rapid rise of ammonia after the soil had been waterlogged, the maximum amount being present in July and August. Thereafter the value decreased and remained at a fairly constant level, except for 2 months after harvest, when the ammonia completely disappeared from East Ravine and was present only in trace in Khoskhana Bye.

Nitrate was absent during the waterlogging period (July to January). In Khoskhana Bye it began to accumulate after harvest, reaching the maximum value of 15.8 p.p.m. in May. But in East Ravine it was present only in trace except on one occasion.

The amount of soluble nitrogen was maximum in July and August. In September it decreased considerably and remained at a low level until a month after harvest, when it suffered further loss in Khoskhana Bye but not in East Ravine.

Hydrolyzable nitrogen was present in much larger amounts than any of the above three forms. It fluctuated irregularly, and this fluctuation could not be correlated with any external factors.

The different forms of alkali-soluble nitrogen remained at a more or less stationary level throughout the year, showing that the different conditions existing in rice fields have little influence on the transformation of the organic nitrogen compounds of the soils.

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# NITRATE FORMATION FROM SOIL ORGANIC MATTER IN RELATION TO TOTAL NITROGEN AND CROPPING PRACTICES

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The most common method of measuring availability of nitrogen in soils is by vegetative tests in field or greenhouse. In addition, the nitrification test has been used rather widely, and attempts have been made to correlate nitrate formation from soil organic matter with the crop-producing power of a soil. A good summary and discussion of earlier nitrification work is given by Waksman (13). His work and that of many others, such as Burgess (2), Brown (1), Gowda (10), and Fraps (4, 5, 8), have shown that usually the more productive soils yield the largest amounts of nitrate, but there have been many exceptions.

In using nitrate formation as a measure of availability of soil nitrogen it is essential, so far as possible, to make the many other factors (6, 7, 8, 14) that limit nitrate formation nonlimiting, or at least uniform. Materials such as lime, phosphorus, and potassium may be added if needed. Likewise, a soil infusion from a fertile soil may be added to supply an active nitrifying flora, particularly if an acid soil is being studied. Physical factors are less readily controlled. Under reasonably good conditions the method seems to be of considerable value on a single soil type subjected to various cropping practices and cultural treatments. The nitrification method, in principle, differs little from vegetative tests, since the same biological agents responsible for release of available nitrogen are utilized in both cases. The end products are merely measured differently.

The primary purposes of the present study were (a) to test further the nitrification method as a means of measuring availability of soil nitrogen, and (b) to determine whether nitrate formation in a given soil type is markedly influenced by past cropping and cultural practices or, on the other hand, is largely independent of such treatments but correlated closely with total soil nitrogen.

## SOIL AND METHODS

The soil studied was Cheyenne fine sandy loam taken from selected field plots at Mandan, North Dakota. The cropping treatments, which have been continuous since 1914, and the chemical analyses of the soils are given in table 1. A thorough study of these soils has shown that the soil on the various portions of the experimental area was originally fairly uniform in texture in the A horizon but was somewhat nonuniform at depths of more than 3 feet. There was considerable variation in the original carbon and nitrogen content of the surface layer. In the present investigations 30 composite soil samples taken from the 0-6-inch layer in May 1947, were studied. These samples included one from a

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single plot of each of 21 cropping treatments shown in table 1, six samples from the plots of the wheat-oats-corn rotation, and three virgin soil samples from near-by areas. Six plots of the one rotation were sampled to obtain information on the degree of variability, apart from the effect of cropping treatment, that may be expected in nitrification results. Where only one plot of a treatment was

TABLE 1  
*Soil treatment and composition*

SOIL NUMBER	CROPPING TREATMENT	pH 1947	ORGANIC CARBON 1943	TOTAL NITRO- GEN 1947	NITRO- GEN LOSS 1914- 1947*
			<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1-6	Wheat, oats, corn	6.7	1.28	0.106	31
7	Wheat, oats, corn	6.6	1.28	0.107	27
8	Wheat, oats, summer fallow	6.6	1.15	0.092	30
9	Oats, wheat, summer fallow	6.5	1.56	0.126	30
10	Wheat, oats, corn	6.7	1.47	0.118	29
11	Wheat, winter rye green manure, oats, corn	6.7	1.42	0.112	34
12	Wheat, summer fallow, oats, corn	6.5	1.53	0.116	28
13	Wheat, sweet clover green manure, oats, corn	6.7	1.27	0.103	25
14	Oats, corn	6.4	1.19	0.101	30
15	Oats, corn, wheat, bromegrass 3 years	6.7	1.34	0.106	31
16	Oats, corn, wheat, alfalfa 3 years	6.7	1.62	0.128	20
17	Wheat, corn	6.5	1.27	0.099	34
18	Wheat, oats, corn, manured	7.2	1.80	0.140	2
19	Wheat, summer fallow (manured), oats, corn	7.0	1.65	0.125	7
20	Wheat, continuous	7.3	1.77	0.140	17
21	Wheat, fallow	6.5	1.73	0.131	28
22	Corn, continuous	7.0	1.43	0.116	34
23	Corn, fallow	6.3	1.23	0.111	34
24	Barley, continuous	6.9	2.01	0.171	14
25	Barley, fallow	6.1	1.93	0.160	26
26	Oats, continuous	6.9	1.41	0.122	10
27	Oats, fallow	6.3	1.41	0.113	25
28	Virgin	7.3	1.82	0.155	0
29	Virgin	6.9	1.85	0.137	0
30	Virgin	6.7	1.74	0.148	0

\* Calculated on the assumption (a) that nitrogen levels in virgin soil were the same in 1913 as in 1943 and (b) that variations in nitrogen content of the virgin soil follow variations in clay content of the soil. These assumptions appear to be reasonably valid for this particular soil.

taken, the replicate chosen for sampling was always the one in wheat or a similar crop (barley or oats), if such a crop was in the rotation. In the corn and fallow treatment the plot in corn was sampled. The soil samples were air-dried immediately and stored in bags until ready for use. The maximum nitrate content of any of the samples when taken was 7 pounds of nitrate nitrogen per 2,000,000 pounds of soil.

The nitrification studies were conducted in 150-ml. Erlenmeyer flasks contain-

ing either 25 or 50 gm. of air-dry soil; 50 gm. were used in the first experiment and 25 gm. in the second. In some cases, where indicated, an addition of 1 per cent finely divided calcium carbonate was made; in a few cases 0.1 per cent ammonium sulfate was added. All soils were inoculated with an infusion of a fertile soil from the same area to eliminate in large part the biological flora as a variable factor. Subsequent tests showed, however, that inoculated and uninoculated soils gave almost identical results. The soils were brought to optimum moisture content (20 per cent) and incubated at 28°C. for varying lengths of time. Water was added at short intervals to maintain constant weight. Nitrate nitrogen, after extraction from the soil, was determined by the phenol disulfonic acid method

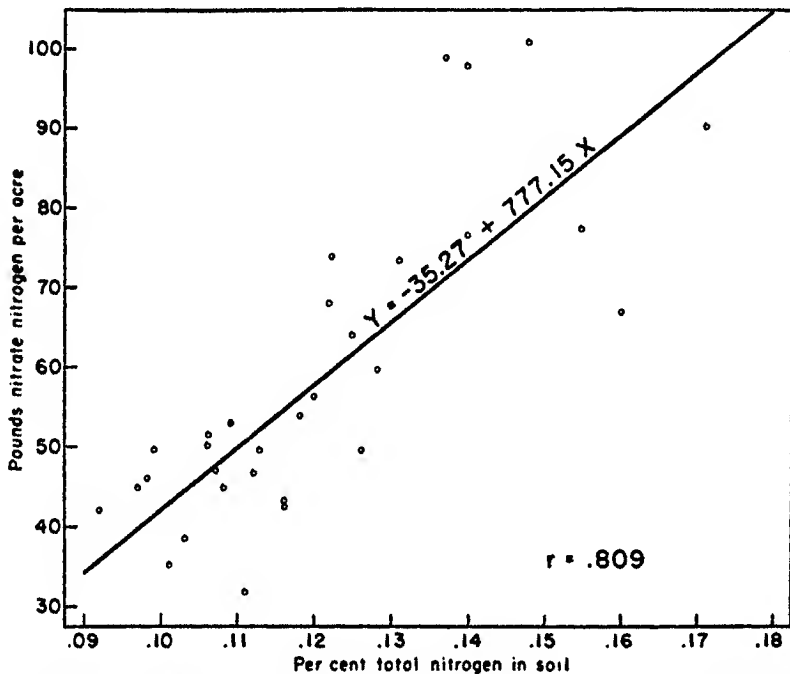


FIG. 1. NITRATES FORMED IN UNLIMED SOILS OF VARYING TOTAL NITROGEN CONTENT DURING 6 WEEKS

using a photometer. In any given experiment only single soil samples were analyzed at each analytical period but most of the tests were repeated nearly a year later.

#### EXPERIMENTAL RESULTS

##### *Nitrate formation from soil organic matter in unlimed soils*

The nitrates formed from the soil organic matter in the untreated soils during the various incubation periods are shown in table 2. The data for the 6-week incubation period are plotted in figure 1 to show how close is the correlation between total soil nitrogen and nitrates formed. In this figure the location of the straight line was determined by the method of least squares. Graphs constructed

TABLE 2  
Nitrate nitrogen formed from soil organic matter in unlimed soils  
during various incubation periods

SOIL NUMBER	TOTAL NITROGEN IN SOIL	NITRATE NITROGEN PER 2,000,000 POUNDS SOIL					
		First experiment				Second experiment	
		21 days	42 days	84 days	161 days	28 days	56 days
	<i>per cent</i>	<i>lb.</i>	<i>lb.</i>	<i>lb.</i>	<i>lb.</i>	<i>lb.</i>	<i>lb.</i>
1	0.108	26.4	45.1	65.7	62.7	47.4	65.8
2	0.120	30.2	56.4	73.4	74.4	49.0	72.4
3	0.109	27.2	53.1	74.3	70.5	59.6	68.8
4	0.106	28.5	51.4	76.8	73.8	51.0	67.6
5	0.097	28.8	45.1	63.1	56.9	60.8	73.6
6	0.098	27.7	46.3	73.7	83.7	63.0	75.2
7	0.107	24.7	46.9	65.7	80.7	46.2	61.6
8	0.092	28.3	42.2	60.6	63.6	44.0	63.2
9	0.126	32.9	49.8	75.8	87.6	51.6	71.8
10	0.118	33.3	54.0	80.8	80.0	53.8	72.0
11	0.112	31.5	46.9	78.5	80.1	52.8	70.8
12	0.116	28.5	42.6	74.4	76.0	48.4	68.6
13	0.103	35.4	38.4	78.0	80.8	51.2	68.4
14	0.101	33.8	35.3	78.9	62.1	42.6	60.2
15	0.106	34.0	50.4	78.0	73.2	49.0	67.6
16	0.128	43.9	59.3	79.3	128.3	57.4	76.0
17	0.099	32.4	49.8	60.4	109.8	44.2	60.4
18	0.140	55.9	76.5	130.7	268.7	76.6	103.0
19	0.125	47.9	63.9	95.5	188.9	69.4	87.4
20	0.140	59.1	96.9	131.9	223.9	84.6	104.6
21	0.131	41.7	73.7	80.7	121.7	56.8	70.4
22	0.116	31.5	42.9	56.9	92.3	38.8	54.2
23	0.111	24.4	32.2	48.4	85.8	32.4	46.8
24	0.171	64.4	90.6	110.6	185.6	95.6	126.0
25	0.160	47.0	67.2	87.0	140.2	94.6	116.2
26	0.122	53.8	67.6	115.4	177.4	72.6	94.2
27	0.113	37.8	49.6	79.0	125.0	49.6	68.6
28	0.155	57.0	77.6	108.4	225.4	89.8	105.8
29	0.137	61.0	98.8	197.8	251.8	88.6	121.4
30	0.148	57.8	100.8	188.8	258.8	87.0	123.8

TABLE 3  
Correlation coefficients for unlimed soils after various incubation periods

CORRELATION*	1ST EXPERIMENT				2ND EXPERIMENT	
	21 days	42 days	84 days	161 days	28 days	56 days
Total nitrogen with nitrate nitrogen formed.....	.833	.809	.594	.758	.834	.849
Per cent decrease in total nitrogen (1914-1947) with nitrate nitrogen formed.....	-.869	-.803	-.855	-.927	-.768	-.810

\* Value required for significance at 1 per cent level is +.463 or -.463.

from the data for the other incubation periods were similar to figure 1. The correlation coefficients are shown in table 3.

Nitrate formation at all incubation periods varied directly with the total nitrogen content of the soil regardless of past agronomic treatment, and negatively with the percentage decrease in total nitrogen during the 33-year cropping period. The correlations were high in view of the many factors known to influence nitrate accumulation. Only a few of the treatments varied greatly from the general trend, and doubtless these variations would have been considerably less if duplicate nitrate determinations on each soil had been made. The rate of nitrate formation in these experiments decreased with time, as expected. This decrease was decidedly more in evidence in the soils of low nitrogen content than in those that had remained at near the original nitrogen content (see figure 3). In fact, the nitrate contents of the low-nitrogen soils after 161 days were often little or no greater than after 84 days. This indicates that under natural conditions not only are the more fertile soils able to supply more nitrate to the crop but the nitrate-supplying power continues over a longer growing season. Other data, presented below, furnish more information upon this point.

Figure 1 shows that whereas nitrate formation is correlated with total soil nitrogen, the nitrates formed per unit of nitrogen present increase with total nitrogen. In going from 0.09 to 0.18 per cent nitrogen the increase in nitrate is not just twice as great (1-fold increase) but 2.8-fold. The corresponding values for the other incubation periods of the first experiment varied between 1.8- and 5.1-fold. Such a tendency might be expected to a limited extent but the observed increases are surprisingly large. Later data help to explain this observation.

#### *Nitrate formation from soil organic matter in limed soils*

The effect of calcium carbonate on nitrate formation is shown in table 4. In figure 2 the data for the 6-week incubation period are plotted against total soil nitrogen. The correlation coefficients of nitrates formed with total soil nitrogen, and also with percentage decrease in total nitrogen during the 33-year cropping period, are given in table 5.

A comparison of nitrates formed on limed and unlimed soils shows a marked stimulating effect of liming even though the soils were not appreciably acid. The extreme variations in pH for the 30 soils, as shown in table 1, were between 6.1 and 7.3, with an average of near 6.7. The effect of lime usually became greater as the incubation period was lengthened. Liming also produced a much greater increase in nitrification in the low-nitrogen than in the high-nitrogen soils. This may be seen from the data in table 4, or more easily by comparison of figure 2 with figure 1. In the first experiment, as already mentioned, an increase of 1-fold in soil nitrogen content caused an increase of 2.8-fold in nitrate formation in the unlimed soils during an incubation period of 6 weeks; in the presence of lime the increase was only 1.2-fold. At the 161-day incubation period the increase was 5.1-fold in the unlimed soils, whereas in the limed soils the increase was only 1.6-fold at the 186-day period.

Figure 3 shows the general effects of liming on nitrification after various incubation periods in the first experiment. In the unlimed soils the rate of nitrate

TABLE 4  
Nitrate nitrogen formed from soil organic matter in limed  
soils during various incubation periods

SOIL NUMBER	TOTAL NITROGEN IN SOIL	NITRATE NITROGEN PER 2,000,000 POUNDS SOIL							
		1st experiment				2nd experiment			
		42 days		186 days		28 days		56 days	
		Nitrate nitrogen	Increase due to lime	Nitrate nitrogen	Increase due to lime	Nitrate nitrogen	Increase due to lime	Nitrate nitrogen	Increase due to lime
	per cent	lb.	per cent	lb.	per cent	lb.	per cent	lb.	per cent
1	0.108	58.3	29	161.7	150	59.8	26	83.0	26
2	0.120	53.0	-6	180.4	138	69.4	42	88.8	23
3	0.109	60.7	14	189.5	165	75.0	26	87.2	27
4	0.106	55.2	7	203.6	173	66.8	31	85.0	26
5	0.097	49.7	10	169.7	191	74.0	22	88.8	21
6	0.098	53.7	16	201.5	130	78.4	24	92.0	22
7	0.107	58.5	25	159.5	86	61.0	32	84.2	37
8	0.092	47.6	13	107.6	66	68.0	55	90.8	44
9	0.126	68.8	33	199.4	116	65.8	28	93.6	30
10	0.118	59.8	11	184.8	129	82.0	52	87.6	22
11	0.112	59.9	28	188.9	133	57.8	9	92.4	31
12	0.116	49.6	16	186.0	139	78.0	61	88.4	29
13	0.103	53.4	39	165.8	101	61.2	20	84.4	23
14	0.101	61.3	74	153.9	145	55.4	30	81.2	35
15	0.106	56.6	12	169.0	127	57.6	18	85.2	26
16	0.128	69.5	17	190.3	32	67.8	18	93.4	23
17	0.099	53.0	6	191.8	52	65.6	48	76.0	26
18	0.140	72.9	-5	343.7	10	59.2	-29	110.2	7
19	0.125	78.5	23	268.9	22	73.0	5	105.0	20
20	0.140	88.7	-9	305.9	20	85.4	1	119.8	15
21	0.131	69.9	-5	216.7	59	71.8	26	96.8	38
22	0.116	39.7	-8	130.3	25	52.2	35	72.4	34
23	0.111	46.8	45	121.8	24	53.2	64	72.4	55
24	0.171	54.8	5	276.6	31	102.0	7	148.4	18
25	0.160	86.8	29	222.0	39	119.4	26	153.0	32
26	0.122	89.8	33	258.4	30	82.2	13	113.4	20
27	0.113	65.8	33	179.0	28	70.8	43	97.4	42
28	0.155	82.0	6	279.4	6	92.2	3	126.6	20
29	0.137	107.8	9	394.8	47	109.4	23	153.8	27
30	0.148	70.6	-30	325.8	16	99.8	15	144.8	17

TABLE 5  
Correlation coefficients for limed soils after various incubation periods

CORRELATION*	1ST EXPERIMENT		2ND EXPERIMENT	
	42 days	186 days	28 days	56 days
Total nitrogen with nitrate nitrogen formed.....	.766	.704	.710	.845
Per cent decrease in total nitrogen (1914-1947) with nitrate nitrogen formed.....	-.740	-.877	-.549	-.756

\* Value required for significance at 1 per cent level is +.463 or -.463.

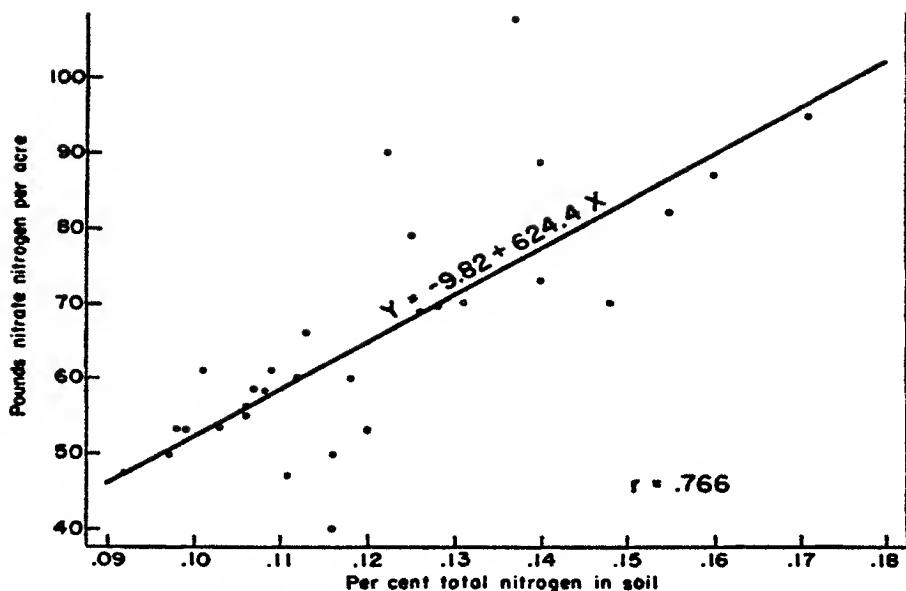


FIG. 2. NITRATES FORMED IN LIMED SOILS OF VARYING TOTAL NITROGEN CONTENT DURING 6 WEEKS

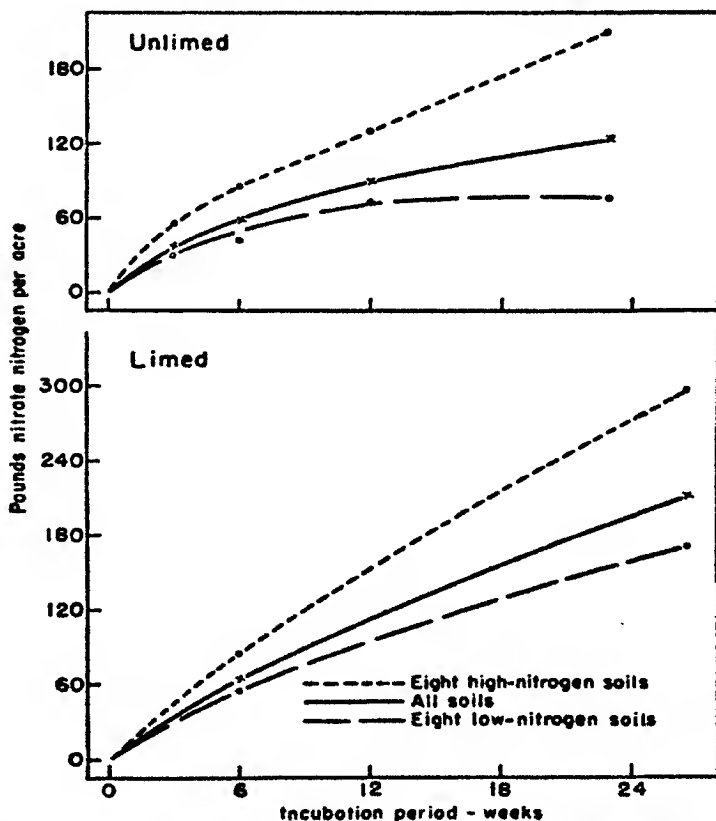


FIG. 3. EFFECT OF LIME ON THE RATE OF NITRATE FORMATION FROM SOILS OF VARYING NITROGEN CONTENT

formation decreased gradually and rather markedly with time. This trend was so marked in the low-nitrogen soils that there was little more nitrate-nitrogen present after 23 weeks than after 12 weeks. In the unlimed high-nitrogen soils the decrease with time was much less. The effect of liming was, in general, to make nitrate formation per unit of soil nitrogen present more nearly the same in all soils regardless of total nitrogen content.

Some of these facts are more clearly brought out by figures 4 and 5, showing the percentage conversion of soil organic nitrogen into nitrates during the various

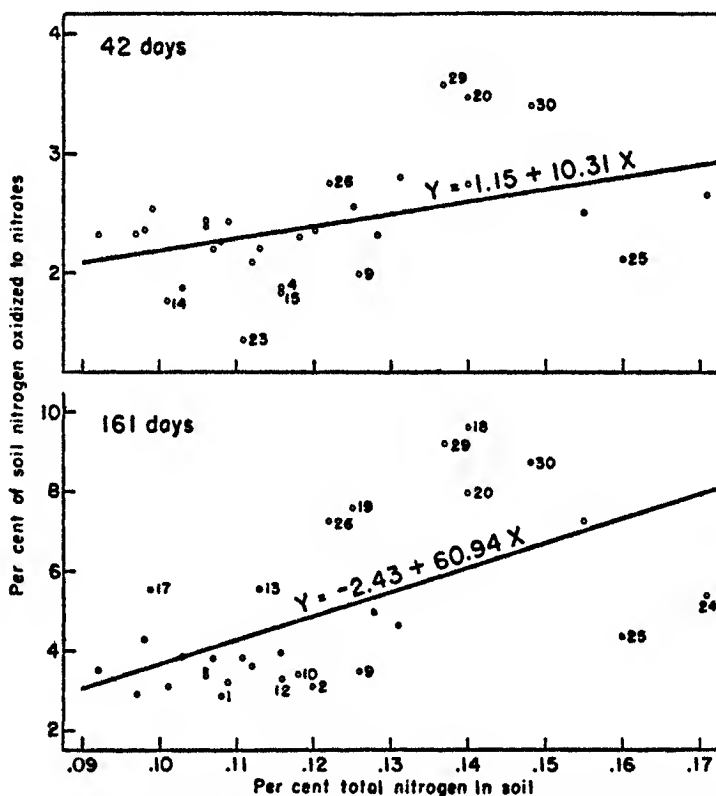


FIG. 4. PERCENTAGE OF NITROGEN IN SOIL ORGANIC MATTER CONVERTED INTO NITRATES IN UNLIMED SOILS IN 42 AND 161 DAYS

incubation periods. In the unlimed soils (fig. 4) the percentage of soil nitrogen converted into nitrates increased rather markedly as the total soil nitrogen increased; in the limed soils (fig. 5) this tendency was not great.

Results for the second experiment were similar to those of the first.

#### *Soil variability as shown by the nitrification experiments*

To determine the reliability of the nitrate production figures as a means of measuring effects due to crop and tillage apart from effects due to natural soil



variations and errors of sampling, six plots (soils 1 to 6) from one of the rotations (wheat, oats, corn) were sampled. Tables 2 and 4 show that nitrate formation was fairly uniform in the soils from these six plots. If the data are expressed as percentage of the total nitrogen converted into nitrates a slightly better estimate of variability is obtained. Table 6 gives the coefficients of variation based on the percentage conversion of the soil nitrogen into nitrates in the six plots. In view of the absence of duplicate nitrification tests on each soil, the variations observed are, seemingly, not excessive. The observed variations are probably no greater

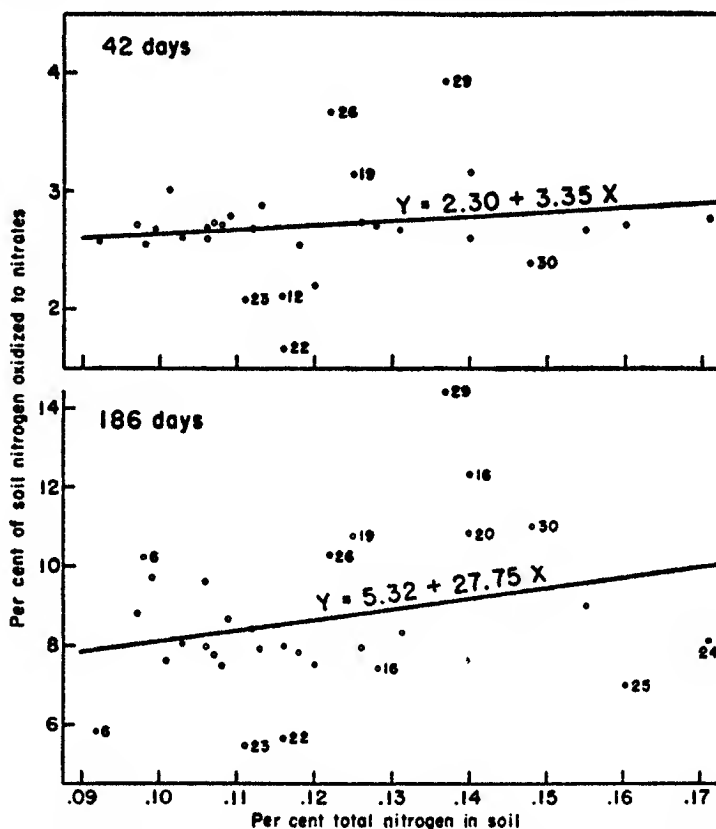


FIG. 5. PERCENTAGE OF NITROGEN IN SOIL ORGANIC MATTER CONVERTED INTO NITRATES IN LIMED SOILS IN 42 AND 186 DAYS

than might be expected from using crop yields as a measure of nitrogen availability. The slightly higher variability of the data of the second experiment as compared with the first experiment is probably due to the greater difficulty in maintaining constant moisture in a 25-gm. soil sample than in a 50-gm. sample.

#### *Nitrate formation from ammonium sulfate*

When the present studies were initiated it was not suspected that lime would be needed on these near-neutral, dry-land soils for a maximum rate of nitrifica-

TABLE 6

*Coefficients of variation for nitrification results for six plots (soils 1 to 6) receiving the same cropping and cultural treatments*

TREATMENT	1ST EXPERIMENT					2ND EXPERIMENT	
	21 days	42 days	84 days	161 days	186 days	28 days	56 days
Unlimed.....	7.7	5.4	8.8	15.4	—	19.7	11.2
Limed.....	—	8.0	—	—	12.7	14.6	9.6

TABLE 7

*Changes in H-ion concentration of soils during nitrification\**

TIME	SOIL, UNTREATED		WITH AMMONIUM SULFATE		
	Nitrates	pH	Nitrates	Nitrification	pH
days	mg./100 gm.		mg./100 gm.	per cent	
<i>Soil 14</i>					
0	0.1	6.4	0.1	—	6.3
14	2.3	6.3	2.6	1.6	5.8
21	3.6	6.1	4.6	5.0	5.7
28	3.8	6.0	8.4	22.1	5.3
56	4.5	5.9	15.3	51.4	4.7
<i>Soil 20</i>					
0	0.2	7.3	0.2	—	7.2
14	4.8	6.9	9.6	22.9	6.2
21	5.8	7.0	16.2	49.1	5.7
28	5.4	7.0	22.4	81.0	5.4
56	7.4	7.0	24.2	80.0	5.3
<i>Soil 21</i>					
0	0.1	6.5	0.1	—	6.5
14	3.4	6.2	3.2	0	5.9
21	4.3	6.1	7.7	16.5	5.7
28	4.4	6.2	9.6	24.8	5.4
56	5.3	6.2	21.8	78.5	4.8
<i>Soil 22</i>					
0	0.2	7.0	0.2	—	6.8
14	3.7	6.6	3.6	0	6.3
21	4.7	6.5	6.9	10.5	6.1
28	4.8	6.6	9.5	22.3	5.6
56	5.8	6.6	20.2	68.6	5.0

\* The analyses were made by Mrs. Janet Doetsch.

tion. In preliminary tests, however, where ammonium sulfate was added, it was observed that soils of lowest nitrogen content were the slowest to nitrify,

just as in the case where no ammonium sulfate was added. It was this observation that first indicated a need for added bases. A similar but more elaborate experiment involving liming showed that in the unlimed soils nitrification of the added nitrogen was again much slower in the soils of low nitrogen content than in those of high nitrogen content. After 8 weeks, however, most of the difference had disappeared. The tendency for nitric acid formation to slow down its rate of production would be much less evident in the field. In addition to a lower rate of nitrogen application the crop is constantly removing both ammonia and nitrate.

#### *Hydrogen-ion changes in soils undergoing nitrification*

Table 7 shows the changes in H-ion concentration as nitrification proceeded. During the 8-week period there were decreases in pH of 0.3 to 0.5 units where soil organic matter was the only nitrogen source, and 1.6 to 1.9 units where ammonium sulfate was added. In considering this decrease in H-ion concentration in the presence of ammonium sulfate it should be borne in mind that although the rate of application used was the usual 100 mgm. per 100 gm. of soil, this is much above that used in agricultural practice.

One of the facts emphasized by these studies is that even though a soil is neutral or nearly so in reaction it may not neutralize the nitric acid formed during nitrification at a sufficiently rapid rate to prevent appreciable retardation of the oxidation process. Any calcium carbonate present, since it has a pH above 7, would be expected to neutralize the nitric acid formed more rapidly and completely than a neutral, base-saturated soil. In Cheyenne fine sandy loam under study, the exchange capacity averaged about 15 m.e., and all samples were nearly base-saturated. Nevertheless, even in the absence of ammonium sulfate the decrease in pH was enough to affect nitrate formation rather markedly. Evidently the nitrification process is more sensitive to slight acidity than is generally supposed.

#### DISCUSSION

The experiments reported here show that in Cheyenne fine sandy loam that had been subjected to various cultural and cropping treatments the main factor that determines the quantity of nitrates formed during a given incubation period, and under ideal conditions for nitrification, is the nitrogen content of the soil. Exhaustive cropping did leave nitrogen that was usually somewhat less available than that in soils where the cropping treatments had tended to maintain the original nitrogen content, but quality and source of organic matter were of less importance than quantity.

The relationship between total soil nitrogen and nitrate formation, or crop production, has been considered by a number of workers, such as Gainey (9), Fraps (3, 4, 5), Fraps and Sterges (8), Sievers and Holtz (12), and Lipman, Burgess, and Klein (11). In general, the published results show a fair correlation between soil nitrogen and nitrate production but many individual soils show wide variations. These variations are due, in part, to use of natural soils without additions of microorganisms, lime, phosphates, or other substances that may be

limiting. The physical properties of a given soil may also be very important. Gainey (9) questioned some of the published results in which soils were grouped on the basis of nitrogen content. He pointed out that such grouped data may show a high correlation between total nitrogen and nitrate formation, whereas if the original values for individual soils are used in calculating the coefficients of correlation the relationship between the two factors may be slight or nil. In the present studies the correlation coefficients given in tables 3 and 5 are based on individual analyses and are, of course, highly significant in all cases. These data, however, were obtained on one soil type variously cropped.

A detailed study of the data presented here, for example, those plotted in figure 5, shows that although most of the results follow the general trend or mean, some variations are rather marked. Comparison of the results for the 42-day incubation period with those for the 186-day period shows that the duration of the experiment is an important factor. Soils 8, 16, 24, and 25 are fairly normal in nitrate production at 42 days but low at 186 days; soils 6, 18, and 20 are normal at 42 days and high at 186 days; and soil 12 is low at 42 days and normal at 186 days. The only soils that are especially low at both incubation periods are 22 and 23. The first of these is from the continuous corn plot and the other is from the alternate corn and fallow plot. Three soils were high at both incubation periods, namely, 19, 26, and 29. The cropping treatments for these in the order given are wheat, fallow (manured), oats, and corn; continuous oats; and virgin. These results indicate a need for more than one incubation period if the nitrification method is to be used to determine availability of soil nitrogen. In general, the data, especially those in figure 5, show that the agronomic treatments that removed the most soil nitrogen, such as continuous corn, tended to leave soil organic matter that was slightly more resistant to attack than normal. On the other hand, treatments that tended to maintain or replenish soil nitrogen, such as continuous small grains, continuous grass (virgin), or additions of manure, resulted in soil nitrogen that was nitrified to a slightly greater extent in a given time. These tendencies are, however, less marked than might have been expected. Even in the extreme case of the virgin soils, two of the three showed reasonably normal nitrification and only one gave results appreciably higher than normal.

The beneficial effect of lime in increasing nitrification, especially in the soils of lowest nitrogen content, was marked. The increases during the 186-day incubation period varied between 6 and 191 per cent with nearly half of the soils showing more than 100 per cent increases. These results were obtained in soils that were above pH 6 and where the low-nitrogen soils were not much more acid than the high-nitrogen soils. Nevertheless, the indications are that the observed benefits of lime were due primarily to the quick and complete removal of the nitric acid as formed. Lime may also have modified the microbial flora but this was probably a minor factor in the present experiments.

If the nitrification method is to be used for characterizing the nitrogen in soil organic matter, conditions must be such that the various biological processes leading to nitrate production may proceed under approximately ideal conditions.

The rate of ammonia formation from the organic matter, and not the rate of nitrate formation from the ammonia, should be the determining factor in the final results. In the present studies this nearly ideal condition was apparently reached where lime was added, but not otherwise. In comparisons of the availability of the nitrogen in a variety of soil types it would be almost impossible to be certain that in all cases the availability of soil nitrogen was the only factor involved; in comparative studies of variously treated soils of the same type the probability of obtaining satisfactory results with the nitrification method is much greater.

#### SUMMARY

Studies designed to determine to what extent nitrate formation can be used as a measure of availability of nitrogen in soil organic matter are reported. The soils studied were all of one type, namely Cheyenne fine sandy loam, but had been subjected to various cropping and cultural treatments for 33 years. The main results are as follows:

The variations in quantities of nitrate formed from soils taken from various plots that had had identical cropping and cultural treatments were no greater than would be expected in corresponding crop yield data.

Nitrate formation from soil organic matter was directly correlated with total soil nitrogen at all incubation periods in both limed and unlimed soils. Nitrates were also negatively correlated with percentage of nitrogen lost during the 33 years of cropping.

In the unlimed soils the nitrates formed per unit of nitrogen present increased markedly as the total nitrogen increased. In limed soils nitrates formed were nearly, but not quite, proportional to total nitrogen present. The lower content of exchangeable bases in the low-nitrogen soils is undoubtedly the explanation for the difference.

Where ammonium sulfate was added to unlimed soils nitrate formation also increased markedly as the total soil nitrogen increased; in the presence of calcium carbonate the percentage nitrification was nearly the same for all soils.

The pH of untreated soils decreased 0.3 to 0.5 pH unit during an incubation period of 8 weeks; where 0.1 per cent ammonium sulfate was added the decrease was 1.6 to 1.9 pH units.

The rate at which soil nitrogen was oxidized to nitrates under ideal conditions was rather high; the mean value for the 42-day period was 2.7 per cent with a high of 3.9 per cent; the mean for the 186-day period was 8.7 per cent with a high of 14.4 per cent.

The present studies indicate that, in a given soil type and under like climatic conditions, thoroughly humified soil organic matter is fairly uniform in quality regardless of past agronomic treatment. The total nitrogen content under these conditions appears to be a rough index of the nitrate-furnishing powers of variously treated soils. Nitrification studies, if conducted under optimum conditions, will furnish additional information on nitrogen availability.

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# EFFECT OF OXYGEN SUPPLY IN NUTRIENT SOLUTION ON AVOCADO AND CITRUS SEEDLINGS<sup>1</sup>

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The oxygen requirements of avocado roots have been studied as part of a general investigation on the causes and control of avocado decline. Field evidence indicates that avocado trees are especially susceptible to overmoist soil conditions, and thus that an adequate oxygen supply at the roots is vital to the health and productivity of these trees.

Virtually no information of a quantitative nature was available heretofore concerning oxygen requirements of avocado roots. Experiments were carried out, therefore, to obtain preliminary information on this subject. Citrus seedlings were included in the experiments for comparison.

## EXPERIMENTAL PROCEDURE

### *Cultural methods*

Aeration experiments on avocado and sweet orange seedlings were run in a greenhouse. The seedlings were germinated in riverbottom sand and then were transferred to nursery solution cultures, where they were kept in readiness for the controlled experiments.

For treatment, the plants were transferred to 20-liter Pyrex bottles, which were covered with brown wrapping paper to exclude light and were fitted with two-hole rubber stoppers to reduce gas exchanges with the atmosphere. A glass aeration tube was inserted through one hole, and a slit was cut from the other hole to the outside of the stopper for convenience in inserting and removing the young plants.

### *Nutrient solution*

The composition of the nutrient solution is shown in table 1. The water used for making up the cultures and for replacing losses due to evaporation and transpiration was taken from an exchange-resin de-ionizing installation. The reaction of each culture was adjusted daily to pH 4.5 with either HNO<sub>3</sub> or KOH as required. Iron was added at the rate of 0.1 p.p.m. three times weekly in the form of ferrous sulfate. The concentration of dissolved oxygen was determined daily by the Winkler method (2).

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<sup>2</sup> Associate in the Experiment Station. This work, which is part of a general investigation on avocado decline, was aided financially by the California Avocado Society. Appreciation is expressed for this help. The author also acknowledges with thanks the counsel of H. D. Chapman in planning the work.

*Oxygen supply*

The concentration of dissolved oxygen in the culture solution was adjusted to various levels ranging from 0.05 to 32 p.p.m. The lowest oxygen level was maintained by bubbling the culture solution with pure nitrogen gas, the highest level by bubbling with pure oxygen gas, and intermediate levels by bubbling

TABLE 1  
*Composition of nutrient solution*

MILLIEQUIVALENTS PER LITER								PARTS PER MILLION					
Ca	Mg	K	Na	NO <sub>3</sub>	PO <sub>4</sub>	SO <sub>4</sub>	Cl	B	Mn	Al	Zn	Fe	Cu
6.0	2.0	2.0	0.1	7.0	1.0	2.0	0.1	0.50	0.50	0.20	0.50	0.10	0.01



FIG. 1. AERATION EXPERIMENT WITH AVOCADO SEEDLINGS

Plants growing in 20-liter Pyrex bottles (left) in the greenhouse. Aeration tubes from these bottles are connected with 2-quart mixing bottles (right). The compressed gases are released through brass needle valves attached to two separate gas lines, lying one on each side of the mixing bottles, and are bubbled through glass tubes submerged in water in these bottles. The cylinder of compressed nitrogen gas (extreme right), with pressure-reducing gauge attached, is connected with one of the gas lines; the other gas line carries compressed air.

with a mixture of either air and oxygen or air and nitrogen gas according to the oxygen concentration desired.

The gases were carried in separate pipe lines and released through brass needle valves into 2-quart mixing bottles. Each gas passed into the bottle through a separate glass tube submerged in water so that the ascending bubbles could be



counted as a guide in controlling the ratio of one gas to the other. (See figure 1 for details.) Before and after treatment all plants were given regular aeration with compressed air.

The length of treatment time at a particular oxygen level was adjusted to meet the needs of the experiment. In the first experiment, 12 different oxygen levels were maintained for 10 days; in the second experiment, three different periods of exposure were observed on seedlings treated at low oxygen level as compared with similar plants kept on regular aeration.

TABLE 2

*Effect of oxygen concentration in nutrient solution on avocado and citrus seedlings (10-day treatment)*

CULTURE NUMBER	OXYGEN CON- CENTRATION		AVOCADO				CITRUS*		
	Mini- mum	Maxi- mum	Root injury	Root growth		Leaf wilt	Root injury	Root growth	
				During treatment	After treatment			During treatment	After treatment
	<i>p.p.m.</i>	<i>p.p.m.</i>							
1	0.05	0.06	Severe	None	None	Delayed	Moder- ate	Poor	Fair
2	0.4	0.4	Moder- ate	None	Poor	Severe	Slight	Poor	Fair
3	0.6	0.7	Slight	None	Poor	Severe	Slight	Poor	Fair
4	1.0	1.1	None	Poor	Fair	None	None	Fair	Fair
5	1.3	1.4	None	Fair	Fair	None	None	Fair	Good
6	1.9	2.3	None	Fair	Good	None	None	Fair	Good
7	2.2	2.9	None	Good	Good	None	None	Fair	Good
8	6.4	6.8	None	Good	Good	None	None	Good	Good
9	8.0	8.6	None	Excellent	Excellent	None	None	Excellent	Excellent
10	10.6	12.4	None	Good	Good	None	None	Good	Good
11	16.0	17.2	None	Fair	Good	None	None	Fair	Good
12	28.8	32.0	None	Stubby	Good	None	None	Stubby	Good

\* None of the citrus seedlings showed leaf wilt.

#### RESPONSE OF PLANTS TO TREATMENT

Table 2 shows the effects of treating avocado and citrus seedlings at different oxygen levels for 10 days; table 3 shows the effects of exposing avocado seedlings to low oxygen level for different intervals. Observations on citrus seedlings are omitted from table 3 because the leaves did not wilt as the result of oxygen deficiency and because root growth was not entirely inhibited even at the lowest oxygen level.

#### *Root injury*

Roots of both avocado and citrus seedlings were injured in cultures having an oxygen concentration of 0.7 p.p.m. or less, but no injury due to oxygen deficiency was found in any of the other cultures (table 2). Injury began at the root tips and progressed up along the fleshy white succulent roots, becoming

more extensive as the time of exposure to low oxygen concentration was increased, and progressing more rapidly at the lowest oxygen concentrations.

TABLE 3  
*Effect of time of exposure to low oxygen concentration in nutrient solution on avocado seedlings*

CULTURE NUMBER	OXYGEN CONCENTRA- TION		ROOT INJURY	ROOT GROWTH		LEAF WILT		
	Minimum	Maximum		During treat- ment	After treat- ment	Interval between treatment and first wilt	Interval between treatment and recovery	Interval between treatment and second wilt
p.p.m.	p.p.m.	hours	hours	days				
12-hour treatment								
1	0.10	0.10	Slight	None	Fair	2	4	—*
2	0.12	0.14	Slight	None	Fair	2	4	—
3	0.08	0.10	Moderate	None	Poor	4	6	—
4	0.10	0.12	Slight	None	Fair	8	10	—
5	0.10	0.12	Slight	None	Fair	2	4	—
24-hour treatment								
6	0.10	0.12	Moderate	None	Poor	2	4	8
7	0.08	0.14	Moderate	None	Poor	4	6	8
8	0.10	0.12	Severe	None	None	2	4	10
9	0.08	0.12	Severe	None	None	6	10	6
10	0.10	0.14	Moderate	None	Poor	8	10	10
96-hour treatment								
11	0.10	0.12	Severe	None	None	8	10	8
12	0.08	0.14	Severe	None	None	2	4	10
13	0.10	0.12	Severe	None	None	2	4	6
14	0.08	0.10	Severe	None	None	4	6	10
15	0.10	0.12	Severe	None	None	2	4	10
Control (normal aeration)								
16	8.20	8.60	None	Excellent	Excellent	—	...	—
17	8.20	8.42	None	Excellent	Excellent	—	...	—
18	8.20	8.40	None	Excellent	Excellent	—	...	—
19	8.24	8.60	None	Excellent	Excellent	—	...	—
20	8.20	8.60	None	Excellent	Excellent	—	...	—

\* Dash indicates no leaf wilt evident.

Injured avocado root tips became constricted or shrunken in the region of cell elongation and turned off-color (fig. 2). At first they turned various shades of pink, yellow, and lavender, but darker discolorations followed a few days later. Injury was more extensive and more severe on avocado roots than on citrus roots, which did not show constricted areas but became very soft and slowly turned

orange-yellow. After several days, injured citrus roots sloughed off. The constricted tips of avocado roots and the soft, pliable tips of citrus roots were detected during the first day of exposure to low oxygen concentrations ranging from 0.05 to 0.7 p.p.m.

Although both avocado and citrus roots showed injury due to oxygen deficiency at a concentration of 0.7 p.p.m., the maximum concentration at which root injury did not occur was 1.0 p.p.m. Evidently the critical value lies somewhere between 0.7 and 1.0 p.p.m.



FIG. 2. NORMAL AVOCADO ROOTS (LEFT) AND INJURED ROOTS (RIGHT)

The dark, shrunken root tips resulted from low oxygen concentration in the nutrient solution.

#### *Root growth*

At oxygen concentrations of 0.05 to 0.06 p.p.m. (table 2), avocado roots failed to grow during and after the 10-day treatment, and all the roots were killed. At slightly higher concentrations, ranging from 0.4 to 0.7 p.p.m., roots failed to grow during the 10-day treatment, but there was some growth, although poor, after treatment. As the oxygen concentration increased, root growth showed improvement, both during and after treatment, until an oxygen level of 8.0 to 8.6 p.p.m. was reached. At higher oxygen levels growth was somewhat retarded, and at the highest level (28.8 to 32.0 p.p.m.), where the solution

was bubbled with pure oxygen gas; the roots became short and stubby with frequent branching.

Roots of citrus seedlings continued to push through the cortex of older roots both during and after all oxygen treatments, including a 10-day exposure to a concentration of 0.05 to 0.06 p.p.m., although growth at this oxygen level was extremely slow. As the oxygen concentration increased, root growth showed improvement, as was observed for avocado roots, until maximum growth was reached at 8.0 to 8.6 p.p.m. At higher oxygen levels there was a decrease in root growth similar to that of avocado roots, and at the highest level the roots became short and stubby, with the same tendency toward frequent branching as that observed for avocado roots.

Roots of avocado did not grow during exposure to low oxygen concentrations (0.05 to 0.7 p.p.m.), but new roots grew from uninjured root areas when regular aeration was supplied after 12 hours' exposure to oxygen levels ranging from 0.08 to 0.14 p.p.m. (table 3). After the 24-hour exposure new roots grew in three out of five cultures; after the 96-hour exposure new roots failed to grow in all cultures, and the plants died.

#### *Leaf wilt*

On warm bright days the immature leaves of the avocado seedlings lost some turgor in all cultures, regardless of oxygen supply, but pronounced wilting was prevalent only where the oxygen concentration was limited to 0.7 p.p.m. or less. The leaves passed through stages of wilting, recovery, and wilting again (table 3). The first wilt included only immature leaves and occurred within 2 to 8 hours after exposure. The leaves regained their normal turgor after 4 to 10 hours and remained turgid for 6 to 10 days. The second wilt included mature and immature leaves but did not occur unless the seedlings were exposed to low oxygen supply for 24 or more hours and did not begin until 6 to 10 days after treatment. This second wilt began with the immature leaves and increased in severeness until all the leaves hung in a limp, flaccid condition, after which the seedlings withered and died.

The second wilt was somewhat delayed at the lowest oxygen level (table 2), for although all the roots had been killed, the leaves continued to absorb water and nutrients for several months. The leaves became leathery and hung partly wilted at a position slightly below the horizontal.

Leaves of citrus seedlings did not wilt at any time during these experiments.

#### DISCUSSION

Although citrus roots were injured under the same conditions of oxygen deficiency (0.05 to 0.7 p.p.m.) that caused injury to avocado roots, new citrus roots continued to push slowly through the cortex of older roots, even at the lowest oxygen concentration observed (0.05 to 0.06 p.p.m.). The work of Leonard and Pinckard (7) showed that the minimum oxygen requirement for cotton root elongation was about 0.3 p.p.m., and that the absence of oxygen did not appear to be very harmful to the roots. When air replaced nitrogen gas (0 per cent

oxygen), new branch roots were initiated, and some of the old branch roots began to grow again.

The studies of Vlamis and Davis (9) indicated that the oxygen requirement of excised roots of tomato, barley, and rice were similar, and yet the three plants reacted differently to anaerobic conditions. The evidence suggests a difference in their capacity to translocate oxygen from the stems to the roots.

Conway (3), using plants of *Cladium mariscus*, found oxygen content high in intact roots but low in excised roots under similar conditions. The results suggest that oxygen is translocated from the aerial part of the plant to the roots. Differences in ability to move oxygen to the roots may partly determine behavior of plants under anaerobic conditions.

Shive (8) found that soybean plants grown in solutions lacking oxygen could persist, although the growth rates were much reduced. He found, also, that the greatest absorption of nitrate nitrogen occurred from nutrient solutions devoid of oxygen, and that absorption of nitrate decreased as oxygen in the nutrient solution increased. Absorption of ammonia by these plants was the reverse of absorption of nitrate. The results were explained as indicating that nitrates were supplying oxygen to the roots under anaerobic conditions. The studies of Haas (5, 6) and of Arnon (1) suggest that nitrate may serve as a source of oxygen for roots in culture solutions of limited oxygen level.

Whatever the mechanism may be for supplying roots with oxygen under anaerobic conditions, it is evident that citrus and avocado roots are not so well equipped as are such plants as rice, soybeans, and cotton; nor are avocados so well adapted to anaerobic conditions as citrus.

Optimum root growth for both citrus and avocado roots was observed at an oxygen concentration of 8.0 to 8.6 p.p.m. Gilbert and Shive (4) reported an optimum oxygen concentration of 6 p.p.m. for soybeans, 16 p.p.m. for tomatoes, and 4 p.p.m. for oats.

Oxygen concentrations near 30 p.p.m. reduced the rate of root growth on citrus and avocados and produced stubby growth with frequent branching. Leonard and Pinckard (7) found that excessive oxygen concentrations (90 per cent or 33 p.p.m.) reduced growth of cotton roots and favored growth of parasites. Gilbert and Shive (4) found that concentrations of 8 and 16 p.p.m. oxygen resulted in chlorosis of soybean leaves when nitrate nitrogen was used. They referred to the chlorotic condition as one of oxygen toxicity.

In the present investigation, no evidence of parasitism or chlorosis was found on either citrus or avocado seedlings as a result of oxygen treatment.

The extreme sensitivity of avocado roots to low oxygen concentration confirms the field evidence that extra precautions must be taken to prevent water-logging of the soil. Overirrigation must be avoided on heavy soils or on soils with imperfect drainage.

#### SUMMARY

Avocado and citrus seedlings were treated in nutrient solutions containing oxygen concentrations ranging from 0.05 to 32 p.p.m. Root tips of avocado

and citrus seedlings showed injury due to oxygen deficiency when the supply of dissolved oxygen was lowered to 0.7 p.p.m. or less. Avocado root tips became constricted in the region of cell elongation and turned dark in color. Citrus root tips were not constricted but became very soft, turned orange-yellow, and finally sloughed off.

Avocado root tips failed to grow during exposure to low oxygen supply but produced new root growth from uninjured root areas after exposure which did not exceed 24 hours. Citrus roots continued to grow at all oxygen levels, although growth was extremely slow at the lowest concentrations.

Leaves of avocado seedlings passed through stages of wilting, recovery, and wilting again, when exposed to low oxygen supply. The first wilt included only immature leaves and occurred 2 to 8 hours after exposure. The leaves regained their normal turgor after 4 to 10 hours. The second wilt, which began 6 to 10 days after treatment, included mature and immature leaves but did not occur unless the seedlings were exposed to low oxygen supply for 24 or more hours. Citrus leaves did not wilt at any time during these experiments.

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## BOOKS

*Annual Review of Microbiology.* Volume 2. Edited by CHARLES E. CLIFTON. Annual Reviews, Inc., Stanford; California, 1948. Pp. 532. Price \$6.

Annual Reviews, Inc., is a nonprofit corporation that devotes itself to the publication of critical reviews designed to effect a systematic coverage of the current literature in certain major fields of science. This volume deals with yeasts, genetics of fungi, bacterial metabolism, metabolism of malarial parasites, growth factors for microorganisms, antibiotics, mode of action of chemotherapeutic agents, inheritance of immunity in animals, complement, nature of antibodies, pathogenic streptococci, spirochetes, neurotropic viruses, bacteria as plant pathogens, chemical disinfectants, microbiology of drinking water and sewage, soil microbiology, and biological nitrogen fixation. The references, which are appended to each chapter, cover the work of some 8,000 scientists. Each chapter has been prepared by a noted authority on the subject covered. Everyone concerned with research or teaching in these fields of study will find this volume an almost indispensable addition to his library.

*Cation Exchange in Soils.* By WALTER P. KELLEY. Reinhold Publishing Corporation, New York, 1948. Pp. 144. Price \$4.50.

This is one of the American Chemical Society's series of chemical monographs. The author has devoted a large part of a long and very useful life to the study of the subject covered in this book. He is thus able to approach the subject from the vantage point of a wide and critical study of all the important investigations in this field of research. The chapter headings are: history of cation exchange, cation-exchange material, cation-exchange equations, principles of cation exchange, exchange capacity and kind of exchangeable cation in various soil types, determination of exchangeable cations, cation exchange in relation to soil properties, and identification and estimation of the clay materials. An extended bibliography of some 175 papers is appended. The author has the capacity to present his material in very lucid and readable form. Every soil scientist will want a personal copy of this book.

*Chemical Fungicides and Plant Insecticides.* Compiled by DONALD E. H. FREAR. The Chronica Botanica Company, Waltham, Massachusetts, and Stechert-Hafner, Inc., New York, 1948. Pp. 153. Price \$5.50.

This is volume 2 of *A Catalogue of Insecticides and Fungicides*. It contains a coding system for the compounds involved and sections on fungicides, insecticides, and miscellaneous products. Appended are a list of references, an author index, a patent list, and an index of chemical compounds. A tremendous amount of work was involved in the preparation of the material for this volume. The author and the publisher deserve the thanks of a great many persons who will profit from their work. The binding is cardboard, but a limited number of copies of the two volumes, bound together in morocco and interleaved with blank paper, are available at \$22.50 each.

*Chemistry and Uses of Insecticides.* By E. R. DE ONG. Reinhold Publishing Corporation, New York, 1948. Pp. 345, figs. 17. Price \$6.

The purpose of this book is to present a broad picture of the development, manufacture, and use of insecticides. The chapters are headed: introduction; copper and its compounds; sulfur and its compounds; miscellaneous inorganic compounds; mineral and other oils; fumigants and fumigation; plant derivatives; synthetic organic compounds; and heat, cold, and radiation as insecticides. The appendix contains a dictionary of insecticides, glossary, legal requirements covering manufacture and sale of insecticides, antidotes, ASMT standards, conversion tables, miscellaneous data, and list of U. S. patents. At the end of each chapter is a long list of references, totaling 1,072 for the entire volume. The book merits a prominent place on the reference shelf of the entomologist and the manufacturer of insecticides.

*Cobalt.* By ROLAND S. YOUNG. Reinhold Publishing Company, New York, 1948. Pp. 181, figs. 41. Price \$5.

This is one of the American Chemical Society's series of chemical monographs. Its purpose is to bring together the widely scattered information on the chemistry and metallurgy of cobalt. The element is discussed under the chapter headings of history, occurrence, metallurgy, chemical and physical properties, in ferrous and nonferrous alloys, in powder metallurgy, in electroplating, in the glass and ceramic industries, catalytic behavior, biological relationships, and methods of analysis. The book contains a great deal of very useful information. The last three chapters are of special interest to those concerned with this and related elements in soil, plant, and microbial systems. Each chapter is well documented with references. The list having to do with cobalt in plant and animal physiology contains 55 titles.

*Comptes Rendus de la Conférence de Pédologie Méditerranéenne.* Maison Berger Levrault, Paris, 1947. Pp. 510. Price 1,600 francs.

This paper-bound volume contains the papers that were given at a summer conference in 1947 on the pedology of certain areas bordering the Mediterranean Sea, with special reference to southern France and Algeria. A number of papers dealing with other soil subjects were also read. The United States was represented by Messrs. J. S. Joffe, Charles E. Kellogg, W. C. Lowdermilk, and Robert L. Pendleton, each of whom presented one or more papers. Some 75 persons were in attendance.

*Diagnostic Techniques for Soils and Crops.* Edited by HERMINIE BROEDEL KITCHEN. The American Potash Institute, Washington, D. C., 1948. Pp. 308. Price \$2.

This book contains detailed discussions of the underlying theories and the practical applications of the various techniques that are employed in the testing of soils and plants for nutrient deficiencies. It contains a historical introduction by Firman E. Bear, and technical discussions by Roger H. Bray, Leland F. Burkhart, Jackson B. Hester, Bert A. Krantz, James E. McMurtrey, Jr., Ivan



E. Miles, Werner L. Nelson, Michael Peech, J. Fielding Reed, Albert Ulrich, and Silvere C. Vandecaveye. The eight chapters deal with chemical methods, correlation of soil tests with crop response, operation of a state soil-testing service, operation of an industrial service laboratory, plant-tissue tests, plant analysis methods and interpretations, biological methods, and visual symptoms of malnutrition. Most of the chapters are followed by lists of references, one totaling 155 and another 175. The book contains a number of illustrations, of which five are in color. An appendix of visual symptoms, with a specific reference for each, covers 35 pages, and is an especially important feature. The book is certain to enjoy a very wide reading. Its value is much greater than the price indicates.

*The Earth and Man.* Revised. BY DARRELL HAUG DAVIS. The Macmillan Company, New York, 1948. Pp. 696, figs. 475. Price \$5.50.

A wealth of highly interesting geographical information is contained in this well-written and excellently illustrated volume. The subject is divided into five parts: the introduction; man: his distribution and numbers; man and environment; the elements of the physical or natural environment; and how man obtains his livelihood. A sixth part, the appendix, has to do with the techniques involved in the study of map projection, earth measurements, map scales, elevation and relief, solar relations, measurement of time, climatic types, weather prediction, and soil classification, together with supplementary climatic maps and miscellaneous tables. One is impressed by the complexity of our civilization, and by the lack of it, and by the difficulties involved in presenting a picture of it. The author has succeeded admirably in outlining and developing the subject. The book merits an important place on the shelves of the agricultural libraries of the United States.

*Factors in Botanical Publication and Other Essays.* By NEIL E. STEVENS. The Chronica Botanica Co., Waltham, Massachusetts, and Stechert-Hafner, Inc., New York. Pp. 88. Price \$2.

This is *Chronica Botanica*, volume 11, number 3, pages 119-206. It consists of 17 essays, written during the period 1920 to 1947, in which the author deals with a variety of topics that are of interest to scientists in general and to plant scientists in particular. These include radicalism and research, obligation of the scientist to the library, botany of New England poets, botany in the Bible, brevity at banquets, fads, bureaucracy, meekness, disease in grains, unfashionable technics in research, plant breeding and plant disease, importance of subject matter, fun in botany, teaching ability, antidote for statistical analysis, objectives in biological courses, and plants in ecology. The appendix gives a list of technical papers that have been published by the author. These essays make interesting and instructive reading.

*Freedom from Want.* Edited by E. E. DETURK. The Chronica Botanica Co., Waltham, Massachusetts, and Stechert-Hafner, Inc., New York. Pp. 78. Price \$2.

The purpose of this fourth number of volume 11 of *Chronica Botanica* is to

survey the possibilities of meeting the world's food needs. The papers were presented as a symposium before the section on agriculture of the American Association for the Advancement of Science. The authors of the several chapters are H. R. Tolley, Robert M. Salter, K. S. Quisenberry, F. B. Morrison, John D. Black, and M. A. McCall. The subjects considered are population and food supply, world soil and fertilizer resources, crop production potentials, animal production, economics of freedom from want, and obligations of science. The foreword was written by Norris E. Dodd, director general, Food and Agricultural Organization of the United Nations. The authors have presented a highly important and interesting picture of the problems of population and food production for our consideration.

*Future Food and Agriculture Policy.* By JOHN D. BLACK AND MAXINE E. KIEFER. McGraw-Hill Book Company, Inc., New York, 1948. Pp. 348, charts 12. Price \$3.50.

This thought-provoking and highly important book is the result of a joint undertaking of the authors, the National Planning Association, the American Farm Economic Association, and the Committee on Food Economics of the Food and Nutrition Board of the National Research Council. It outlines a program for the next 10 years. After defining the situation as it existed in 1947, the book considers several phases of the problem, including population growth, agricultural instability, low-income farmers, malnourished groups, food needs of the United States, food-producing capacity of the United States, soil conservation, world food needs, and food distribution. The third part deals with food and agricultural programs of the United States and certain other countries. Part four has to do with the problem of execution of such programs. After consideration of food in relation to population, the conclusion is reached that "adjustment of population to resources is also necessary." The subject is one of vital interest to everyone. The presentation is excellent. Probably the most important chapter is the one that deals with "a balanced food and agriculture program for the United States," in which the problem of control of agricultural production is dealt with. The book merits, and no doubt will receive, wide reading and study.

*Hormones and Horticulture.* By GEORGE S. AVERY, JR. AND ELIZABETH B. JOHNSON. McGraw-Hill Book Company, Inc., New York, 1947. Pp. 326. Price \$4.50.

"A chemical revolution is sweeping through the agricultural world. . . . For the first time, man can change the pattern of growth and development of plants, can retard growth here or speed it there." These sentences constitute the introductory paragraph to this very stimulating book. The several chapters deal with chemicals in relation to the rooting of cuttings, thinning of blossoms, control of preharvest drop of fruit, treatment of seeds, miscellaneous growth phenomena, weed control, breaking, prolonging, and inducing dormancy, and production of new plant varieties. Of special interest are the 70 pages listing the hormones that have been found most effective in improving the rooting of cuttings. The book is well illustrated and contains nearly 700 references on the

work that has been done with the great variety of chemicals now being employed in horticultural and agricultural practice. It is a very useful book to have at hand.

*The Literature on Streptomycin.* By SELMAN A. WAKSMAN. Rutgers University Press, New Brunswick, New Jersey, 1948. Pp. 112. Price \$3.

The first announcement of the isolation of streptomycin was made January 1, 1944. Since that date, a surprisingly large number of papers on this subject have been published. Of these, 1,171 are presented, by author, title, and journal, in this book. A reprint of the first official announcement of the isolation of streptomycin is also included. In addition, some general references to Actinomycetes and their antagonistic properties and to streptothricin are given.

*Mineral Nutrition of Plants and Animals.* By FRANK A. GILBERT. University of Oklahoma Press, Norman, 1948. Pp. 131, figs. 31. Price \$2.75.

This is a short summary of the work that has been done in trying to determine the usefulness or the harmfulness of phosphorus, calcium, magnesium, potassium, sulfur, iron, copper, cobalt, manganese, zinc, iodine, boron, molybdenum, aluminum, silicon, sodium, chlorine, fluorine, arsenic, lead, and selenium to plants and animals, with some supplemental observations on human nutrition. A bibliography of 130 papers is appended. The illustrations are well chosen. The material makes interesting and informative reading. The book is useful for reference purposes, but a much more extended discussion is suggested for a second edition, if this should ever be published.

*Outlines of Physical Chemistry.* By FARRINGTON DANIELS. John Wiley & Sons, Inc., New York, 1948. Pp. 713, figs. 164. Price \$5.

Many things about physical chemistry have been learned since the publication, in 1913, of the first edition of Frederick H. Getman's book, of which this is the successor. The original volume was not so large as this, but the material in it was exceptionally well presented. Farrington Daniels has succeeded admirably in retaining much of the lucidity of expression of Getman's text. He has extended the concepts to cover modern developments in this very interesting and important field of chemical science. As an aid to better understanding of the principles involved, a set of problems is appended to each chapter. References to other texts for supplemental reading are also given. The appendix shows the derivations of the more important equations mentioned in the text. It also includes tables of physical-chemical constants and atomic weights. The final chapter is a modern presentation of atomic and nuclear structure. The book as it now stands is essentially an entirely new one that will probably find wide use as a text.

*Soil Science Society of America Proceedings, 1947.* The Soil Science Society of America, G. G. Pohlman, Secy.-Treas., Morgantown, West Virginia, 1948. Pp. 539. Price \$7.50.

This is volume 12 of the proceedings of the Society. It gives the officers for 1947, the minutes of the meetings for that year, the papers presented, and the

officers and standing committees for 1948. The general program consisted of three papers, one on the problem of feeding India's four hundred millions, by A. T. Sen; a second on some problems of agriculture in Western Europe, by M. D. Weldon; and the third on soils and land use in China, by J. Lossing Buck. In addition, 111 papers on soil physics, chemistry, microbiology, fertility, genesis, morphology, cartography, and technology were read. The volume contains a wealth of material for those interested in soil science. It might well be made required reading for every graduate student majoring in this field of research.

*Starting and Managing a Farm.* By C. M. HAMPSON. McGraw-Hill Book Company, Inc., New York, 1948. Pp. 250. Price \$2.60.

The author of this book considers the problem from the point of view of the part-time farmer and the man who farms full-time for a living. The first part tells what to expect from farming. It points out that small farms do not pay well and tells why. It gives some of the difficulties in getting started as a farmer and some of the opportunities for those who can qualify. The advantages of part-time farming are said to be in the savings in rent and groceries and the greater degree of security in times of depression. One can go a long way on a very little cash in time of need. As to the full-time farmer, the point is made that prices are high and that this may be a poor time to buy a farm. The advantages of a large farm of level land in a good neighborhood are pointed out. When well-managed, such a farm should pay well in money made and in the joys that accrue to those who like to live on the land. The book is exceptionally well written, it contains many excellent illustrations, and it is full of very good advice to those who would like to farm.

*Sugar—Facts and Figures.* Published by the United States Cuban Sugar Council, New York, 1948. Pp. 159, charts 21.

The facts and figures presented in this volume make very interesting reading. They show that our per capita consumption of refined sugar for 1947 was 96.4 pounds, and that the total consumption of raw sugar in the United States was 7,389,000 tons. The several chapters deal with how and where sugar is produced, world sugar consumption and trade, where the United States gets its sugar, sugar consumption, sugar legislation, sugar prices, Cuba and its sugar industry, and our trade with Cuba. The appendix gives, in excerpt or in full, the sugar acts of 1934, 1937, and 1948, general agreements on tariffs and trade, exclusive agreement between the United States and Cuba, reciprocal trade agreements, international sugar agreements, Philippine trade act of 1946, some important letters about sugar, chronology of sugar controls during World War II, and tables of equivalencies of weights and areas used in the Cuban sugar industry. The book is well illustrated and is an important addition to the literature in this field.

THE EDITORS.

## NEWS NOTES

### NATIONAL RESEARCH COUNCIL COMMITTEES ON INTERRELATIONS OF PLEISTOCENE RESEARCH AND ON THE STUDY OF EOLIAN DEPOSITS OF THE UNITED STATES AND CANADA

Pedologists have long been aware of the outstanding contributions of Pleistocene deposits to the soil wealth of the world. A comparison of maps of Pleistocene deposits with maps showing concentrations of human populations reveals instantly that a very large proportion of the world's inhabitants must derive their food supply from soils developed in Pleistocene materials. For more than 50 years, pedologists have been drawing attention to the interrelations of soils with Pleistocene deposits and with their climatic and biotic environments. Greatest emphases on these phases have been within the last 30 years.

These facts have prompted Dr. Richard Foster Flint, Chairman of the Committee on Interrelations of Pleistocene Research of the Division of Geology and Geography, National Research Council, to recognize the field of soil science in his committee. The committee was organized in June, 1947, and held its first meeting at Yale University on April 5-6, 1948. The following list of committee members with the field of specialization of each gives a good idea of the scope of committee's activities:

Edward S. Deevey, Jr., Department of Biology, Yale University (biogeography); Loren C. Eiseley, Department of Anthropology, University of Pennsylvania (anthropology and new-world archeology); Richard Foster Flint, Department of Geology, Yale University, chairman of the committee; Claude W. Hibbard, Museum of Paleontology, University of Michigan (vertebrate paleontology); Chauncey D. Holmes, Department of Geology, University of Missouri (glacial erosion and sedimentation); Helmut E. Landsberg, Committee on Geophysical Sciences, Research and Development Board, Washington, D. C. (meteorology and climatology); Hallam L. Movius, Jr., Peabody Museum of Archaeology and Ethnology, Harvard University (old-world archeology); Fred B. Phleger, Jr., Department of Geology, Amherst College (oceanography and sea-floor geology); Louis L. Ray, U. S. Geological Survey, Washington, D. C. (glacial stratigraphy: alpine glacial geology); H. T. U. Smith, Department of Geology, University of Kansas (eolian features; frozen ground; stream terraces); and James Thorp, Division of Soil Survey, U. S. Department of Agriculture, 204 Nebraska Hall, University of Nebraska, Lincoln 8, Nebraska (soil science).

The chairman of the committee expects that other fields of interest will be added as need arises. The chief objective of the committee is to facilitate exchange of ideas and coordination of efforts in the various fields of specialization. The soil science representative on the committee would welcome correspondence with other pedologists that would give suggestions as to how the committee could best serve the needs of soil science.

At the meeting of the Committee on Interrelations of Pleistocene, one of the first problems discussed was that of the extent and character of eolian Pleistocene

deposits of North America. It was brought out that these deposits comprise one of the largest groups of materials from which productive soils of the continent are developed. It was also emphasized that a great variation in the character of soils developed from eolian deposits has been brought about by factors of the environment.

The committee recognized that the study of eolian deposits was a large field in itself and one that justified organization of a new committee. Accordingly a proposal was made to Dr. Arthur Bevan, Chairman of the Division of Geology and Geography of the National Research Council, that a committee be organized for the study of eolian deposits in the United States, Canada, and Alaska. The chief objective of the committee would be to prepare a map, probably on a scale of 1/5,000,000, showing the distribution and character of eolian deposits of the continent and, so far as possible, bringing out the relations between these deposits and the important kinds of soils developed from them. It was recognized that pedologists should have a leading part on the new committee because of the great amount of work they have done on the study of loess and eolian sands of the world.

The new committee is organized under the co-chairmanship of H. T. U. Smith, Professor of Geology at Kansas State University, who has a major interest in the study of eolian sands, and James Thorp, Principal Soil Correlator for the Great Plains States, Division of Soil Survey, U. S. Department of Agriculture.

The committee is bending its efforts toward getting all possible information on the character, thickness, and geographic extent of eolian silt (loess and loess-derived soils), eolian sand, and eolian clay. It is recognized that no one person has a full grasp of the present knowledge of these deposits, and it is urged that those who are willing to contribute to the map on eolian deposits of North America get in touch with one of the members of the committee:

Mark Baldwin, Rural Route 3, Albany, Georgia (soil science), now retired, former chief inspector, Division of Soil Survey, U. S. Department of Agriculture; W. Earl Bowser, Dominion Soil Survey, University of Alberta, Edmonton, Alberta, Canada (soil science) alternate for H. C. Moss; Richard Foster Flint, Professor of Geology, Yale University, New Haven, Connecticut, also representing U. S. Geological Survey (Pleistocene geology); Lawrence M. Gould, President, Carleton College, Northfield, Minnesota (Pleistocene geology); Harold C. Moss, Dominion Soil Survey, Soils Department, University of Saskatchewan, Saskatoon, Saskatchewan (soil science); E. C. Reed, Associate-Chief, Department of Geology, 108 Nebraska Hall, University of Nebraska, Lincoln 8, Nebraska (subsurface geology); Guy D. Smith, Soil Correlator U. S. Department of Agriculture, Landscape Architectural Building, Iowa State College, Ames, Iowa (soil science and Pleistocene geology); H. T. U. Smith, University of Kansas, Lawrence, Kansas (Pleistocene geology), co-chairman of committee; and James Thorp (soil science and Pleistocene geology), co-chairman of committee.

JAMES THORP.

# FLUORINE: ITS TOXICITY TO PLANTS AND ITS CONTROL IN SOILS<sup>1</sup>

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*New Jersey Agricultural Experiment Station*

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The ill effects of air pollution by fluorine or hydrofluoric acid fumes on vegetation have been amply demonstrated in the field and by controlled experiments.<sup>2</sup> What effects these fumes may have on the crop-producing capacities of soils have not been so clearly shown. For 2 years, greenhouse studies have been carried on at the New Jersey Agricultural Experiment Station to determine at what concentration in the soil F becomes toxic to plants and what corrective measures can be applied to advantage when this point has been reached.

## EXPERIMENTS WITH SODIUM FLUORIDE

### *Buckwheat*

In the first experiment, buckwheat plants were grown in pots that had been filled with Sassafras loam and sandy loam soils. Three pH levels (6.5, 5.5, and 4.5) and three of  $P_2O_5$  (100, 200, and 400 pounds per acre<sup>3</sup>) were employed. Fluorine was supplied at rates of 0, 5.5, 11, 22, 45, 90, 180, and 360 p.p.m. as NaF. The NaF was applied in solution and was thoroughly mixed with the entire volume of soil. Standard quantities of N and K, as well as of the minor elements, were added to all pots. All treatments were in duplicate. The plants thus produced were dried between 45° and 50°C.

The dry-weight yields of the buckwheat plants are recorded in table 1. The data show that concentrations of F up to 180 p.p.m. did not cause serious reduction in crop yield when the pH value of the soil was maintained at 6.5. On the sandy loam, additions of 180 p.p.m. F did not injure buckwheat plants at pH values of 5.5 or above, but at 4.5 they were definitely harmful. On the loam, 360 p.p.m. F proved injurious even at pH 6.5 and was extremely toxic at 4.5. The plants grew better on the soils receiving 400 pounds  $P_2O_5$  per acre than on those receiving only one fourth that amount.

Plants from the 0, 180, and 360 p.p.m. F treatments, and to which  $P_2O_5$  had been supplied at the 200-pound-per-acre rate, were analyzed for F<sup>4</sup> (table 2). The

<sup>1</sup> Journal Series paper of the New Jersey Agricultural Experiment Station, Rutgers University—the State University of New Jersey, department of soils.

<sup>2</sup> De Ong, E. R. Injury to apricot leaves from fluorine deposit. *Phytopath.* 36: 469-471. 1946.

Johnson, F., Miller, V. L., and Allmendinger, D. F. Hydrogen fluoride injury to prune trees in Washington. (Abs.) *Phytopath.* 37: 362. 1947.

Miller, V. L., Johnson, F., and Allmendinger, D. F. Fluorine analysis of Italian prune foliage affected by marginal scorch. *Phytopath.* 38: 30-37. 1948.

Unpublished data, N. J. Agricultural Experiment Station, 1948.

<sup>3</sup> In this and all subsequent cases, the term *acre* refers to 2,000,000 pounds of soil.

<sup>4</sup> Leone, I. A., *et al.* Some effects of fluorine on peach, tomato, and buckwheat when absorbed through the roots. *Soil Sci.* 66: 259-266. 1948.

F content of plants grown on the loam at pH 4.5, without added F, was 13 times as high as that of the plants on the sandy loam. The F content of plants produced on soils to which 180 and 360 p.p.m. of the element had been applied was

TABLE 1

*Dry weight of buckwheat plants grown on soils at different levels of pH and  $P_2O_5$*

F ADDED	WEIGHT OF PLANTS*								
	pH 6.5; $P_2O_5$ lb./A.			pH 5.5; $P_2O_5$ lb./A.			pH 4.5; $P_2O_5$ lb./A.		
	100	200	400	100	200	400	100	200	400
Sandy loam									
p.p.m.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
0	15	14	15	11	14	13	9	9	12
5.5	12	—	—	11	—	—	8	—	—
11	10	12	14	11	13	15	9	12	10
22	13	—	—	12	—	—	8	—	—
45	13	15	10	13	13	15	10	9	10
90	13	—	—	13	—	—	9	—	—
180	13	14	16	14	10	13	7	8	8
Loam									
0	12	11	8	12	8	8	8	5	6
11	13	—	—	9	—	—	6	—	—
22	14	9	10	10	6	6	5	5	5
45	12	—	—	12	—	—	4	—	—
90	13	10	12	11	8	5	2	6	5
180	11	—	—	9	—	—	2	—	—
360	6	5	7	7	5	7	1	3	1

\* In two pots.

TABLE 2

*Fluorine (F) content of buckwheat plants grown on soils\* under different fluorine treatments*

F ADDED	FLUORINE CONTENT OF PLANTS					
	Sandy loam			Loam		
	pH 6.5	pH 5.5	pH 4.5	pH 6.5	pH 5.5	pH 4.5
p.p.m.	p.p.m.	p.p.m.	p.p.m.	p.p.m.	p.p.m.	p.p.m.
0	0	10	15	7	10	196
180	42	100	651	7	175	1170
360	—	—	—	59	167	1280

\* The sandy loam and loam originally contained 113 and 181 p.p.m. F, respectively.

very high at pH values of 4.5, but when these values were raised to 5.5, by the use of lime, the plants contained only one sixth to one seventh as much F. At pH 6.5, the F content was further reduced. Doubling the phosphate application reduced the F content of the crop in some cases (not shown in table).



*Tomatoes*

In this experiment, F levels below 22 p.p.m. were omitted, and a 720-p.p.m. rate was added. The  $P_2O_5$  levels were raised to 200, 300, and 500 pounds per acre. The plants thus produced were dried between 45° and 50°C. From the yields (table 3), it is evident that, on the sandy loam, at a pH value of 6.5, injury occurred at 360 p.p.m. F. The higher the phosphate level at this F concentration, the greater the yields. At a pH value of 5.5, a significant drop in yield occurred at 360 p.p.m. F, and a very marked drop at 720 p.p.m. Additional phosphate gave significantly higher but not satisfactory yields at 720

TABLE 3

*Dry weight of tomato plants grown on soils at different levels of pH and  $P_2O_5$*

F ADDED	WEIGHT OF PLANTS*								
	pH 6.5; $P_2O_5$ , lb./A.			pH 5.5; $P_2O_5$ , lb./A.			pH 4.5; $P_2O_5$ , lb./A.		
	200	300	500	200	300	500	200	300	500
Sandy loam									
p.p.m.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
0	36	42	36	30	26	33	17	13	20
22	35	—	—	28	—	—	11	—	—
45	36	41	44	33	31	29	15	20	23
90	37	—	—	33	—	—	14	—	—
180	41	37	31	29	31	27	16	19	17
360	12	16	30	6	—	—	2	—	—
720	8	—	—	2	3	20	0	2	2
Loam									
0	44	45	39	30	41	48	10	13	19
22	38	46	40	32	44	35	12	12	18
45	38	—	—	27	—	—	5	—	—
90	37	43	30	31	44	39	7	13	17
180	37	—	—	24	—	—	3	—	—
360	47	41	44	30	28	30	1	4	6
720	28	—	—	12	—	—	0	—	—

\* In two pots.

p.p.m. F. On the loam, definite injury did not occur at either pH 5.5 or 6.5 until 720 p.p.m. F was reached. Extra phosphate increased the yields at 22 and 90 p.p.m. F, but not at 360 p.p.m. Since extra phosphate tended to increase the yield of tomatoes on the pots receiving no F, its good effect in overcoming toxicity of this element was not very apparent in this test.

Yields on the sandy loam were usually much lower at pH 4.5 than at higher pH values. Again the injury to plants, as reflected in yields, was not definite until 360 p.p.m. F was reached. The exact point of serious toxicity was somewhere between 180 and 360 p.p.m. F, and at 720 p.p.m. all plants were killed. At 45 and 180 p.p.m. F, extra phosphate produced material increases in yield. On

the loam, yields were also much lower at a pH value of 4.5 than at the higher pH values. They dropped off sharply at 180 p.p.m. F, and all plants were killed at 720 p.p.m. Extra phosphate proved beneficial at all F concentrations.

These experiments show that the degree of toxicity of F depends on the type of soil and on its lime and phosphate levels, as well as on the nature of the plant that is being grown.

The leaves of some of the tomato plants from the soils receiving  $P_2O_5$  at the 200-pound-per-acre rate were analyzed for F (table 4). Those from plants grown on the loam at pH 4.5 contained more of the element than did those from plants grown on the sandy loam. This was to be expected, since the loam contained 68 p.p.m. more F. When the pH values were raised to 5.5 and 6.5, the amount of F in the leaves was greatly reduced. Marked increases in F values were obtained at pH 4.5 from the use of 90, 180, and 360 p.p.m. F. On the sandy loam, at pH 5.5, the content of F in the leaves was reduced to about one third that at pH 4.5; at pH 6.5, it was not much higher than where no F had been added.

TABLE 4

*Fluorine (F) content of leaves of tomato grown on soils under different fluorine treatments*

F ADDED	FLUORINE CONTENT OF PLANTS					
	Sandy loam			Loam		
	pH 6.5	pH 5.5	pH 4.5	pH 6.5	pH 5.5	pH 4.5
<i>p.p.m.</i>	<i>p.p.m.</i>	<i>p.p.m.</i>	<i>p.p.m.</i>	<i>p.p.m.</i>	<i>p.p.m.</i>	<i>p.p.m.</i>
0	30	27	49	2	24	76
90	—	—	—	—	—	527
180	37	56	153	20	103	—
360	46	239	782	49	273	—

Doubling the quantity of  $P_2O_5$  (not shown in table) applied to the soil tended to lower still further the F content.

#### EXPERIMENTS WITH HYDROFLUORIC ACID

##### *Tomatoes—crop I*

The use of dilute HF simulates more nearly than that of NaF, conditions in the field where crops are subject to fumes from industrial plants. Consequently, a new experiment was set up in which HF was applied to the surface of the soil in ten separate increments, at 1-week intervals, to supply a total of 0, 90, 180, 360, 720, and 1,440 p.p.m. F for the entire volume of soil. The concentrations were, of course, much greater than these in the surface zone. The same two soils were used as in the previous experiments, at three pH values and two  $P_2O_5$  levels. Before any HF was applied, the tomato seedlings were allowed to develop to a height of 4 to 6 inches.

Twenty-four hours after the first application, the tomato plants receiving the greatest quantity of HF showed definite curling and wilting of the leaves, with spotted, chlorotic areas between the veins. The injury was more severe on the

low pH value soils and on the sandy loam. After the second increment of HF, burning of the edges of the leaves, followed by necrosis, was noted on plants receiving 720 p.p.m. F. As the applications of HF were continued, the injury resulting from the earlier applications did not always increase, because the plant roots were extending into the lower parts of the pot where they were out of the zone of greatest HF concentration. After the eighth increment, the fruit from the two highest F treatments showed brown spots, resembling blossom-end rot, which gradually increased in size. Necrosis began at the tops of the plants and worked downward on the stems.

The total yields of the plants from this experiment are given in table 5. In nearly all cases the yields were highest on the soils receiving no HF. Yields usually decreased progressively as the amount of HF increased and as the pH decreased. At the highest pH value the loam produced a higher yield than the

TABLE 5

*Dry weight of tomato plants—crop I—grown on soils at different levels of pH and P<sub>2</sub>O<sub>5</sub>*

F ADDED	WEIGHT OF PLANTS*											
	Sandy loam						Loam					
	pH 6.3; P <sub>2</sub> O <sub>5</sub> , lb./A.		pH 5.5; P <sub>2</sub> O <sub>5</sub> , lb./A.		pH 5.0; P <sub>2</sub> O <sub>5</sub> , lb./A.		pH 6.5; P <sub>2</sub> O <sub>5</sub> , lb./A.		pH 5.5; P <sub>2</sub> O <sub>5</sub> , lb./A.		pH 5.0; P <sub>2</sub> O <sub>5</sub> , lb./A.	
	200	400	200	400	200	400	200	400	200	400	200	400
p p.m.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
0	79	86	71	79	59	60	84	84	72	74	66	62
90	77	84	58	65	42	52	81	86	55	86	54	58
180	71	79	54	64	43	44	86	81	54	76	53	53
360	66	86	55	59	45	47	86	81	55	63	44	53
720	62	67	47	42	14	31	71	62	41	45	40	36
1440	23	31	13	12	1	10	48	30	13	23	13	21

\* In two pots.

sandy loam, even with the higher application of HF. In most cases, doubling the amount of P<sub>2</sub>O<sub>5</sub> increased the yield at each HF level and within each pH value. At 1,440 p.p.m. F, the plants were severely injured and gave very low yields on the sandy loam. On the loam the plants were also severely injured at this high HF level, but the yields were considerably higher than on the sandy loam, especially at the high pH value. Injury to the tomato fruit was very apparent at the 720 and 1,440 p.p.m. F levels.

Twenty-four samples of leaves from this experiment were analyzed for F. Root distribution, in relation to zones of high F content in the soils, are believed responsible for the great variability in F absorption. Where 720 p.p.m. F was added to the loam, at low pH values, 2,973 p.p.m. of the element was found in the tomato leaves.

#### *Tomatoes—crop II*

The roots from crop I were removed, and the soils were thoroughly mixed and allowed to remain idle during summer. In fall, a fertilizer solution supplying

100 pounds N, 200 pounds  $P_2O_5$ , and 200 pounds  $K_2O$  per acre was applied and thoroughly mixed with the soils, which were then brought up to an optimum moisture level and seeded to tomatoes. The plants were harvested at about the blossom stage, and yields are recorded in table 6.

TABLE 6

*Dry weight of tomato plants—crop II—grown on soils at different levels of pH and  $P_2O_5$*

F ADDED	WEIGHT OF PLANTS*											
	Sandy loam						Loam					
	pH† 6.3 to 5.0; $P_2O_5$ , lb./A.		pH† 5.5 to 4.7; $P_2O_5$ , lb./A.		pH† 5.0 to 4.5; $P_2O_5$ , lb./A.		pH† 6.5 to 5.2; $P_2O_5$ , lb./A.		pH† 5.5 to 4.7; $P_2O_5$ , lb./A.		pH† 5.0 to 4.5; $P_2O_5$ , lb./A.	
	200	400	200	400	200	400	200	400	200	400	200	400
p.p.m.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
0	34	32	18	18	10	21	55	55	45	50	43	46
90	23	22	17	4	5	10	49	54	50	49	16	39
180	26	23	8	9	1	4	53	49	32	44	3	15
360	17	7	3	2	0	1	46	41	2	7	1	2
720	1	6	0	0	0	0	5	12	0	0	0	0
1440	0	0	0	0	0	0	0	0	0	0	0	0

\* In two pots.

† pH values at start of first experiment (crop I, 1946) and at end of second experiment (crop II, 1948).



FIG. 1. EFFECT OF F AS HF ON TOMATOES ON SASSAFRAS LOAM AT pH 6.5

Left to right: 0, 90, 180, 360, and 720 p.p.m. F

Although the pH values of the soils at the end of the experiment (2 years) had dropped to a relatively low point from the original, three distinctly different pH levels still remained. At the high pH value on the loam the toxic effects from HF, as measured by plant yields, were almost negligible up to a concentration of 180 p.p.m. F. Very little toxicity was noted even at 360 p.p.m. F, but above that concentration yields fell off rapidly (figs. 1 and 2). In the sandy



FIG. 2. EFFECT OF F AS HF ON TOMATOES ON SASSAFRAS LOAM AT pH 5

Left to right: 0, 90, 180, 360, and 720 p.p.m. F

TABLE 7

*Fluorine content of leaves of tomato—crop II—grown on soils under different fluorine treatments*

P <sub>2</sub> O <sub>5</sub>	F ADDED	FLUORINE CONTENT OF LEAVES		
		pH 6.3	pH 5.5	pH 4.5
Sandy Loam				
lb./A.	p.p.m.	p.p.m.	p.p.m.	p.p.m.
200	0	5	22	29
	90	19	33	56
	180	42	134	66
	360	242	327	—
	720	678	—	—
400	0	14	13	19
	90	17	42	42
	180	25	67	73
	360	78	218	437
	720	367	—	—
Loam				
200	0	7	15	23
	90	8	27	78
	180	16	89	190
	360	91	480	1008
	720	276	—	—
400	0	9	15	23
	90	19	25	56
	180	21	48	219
	360	67	350	471
	720	600	—	—

loam, 180 p.p.m. F was not harmful at the high pH values, but higher concentrations were definitely injurious. As in the earlier experiments, doubling the amount of applied P proved most effective in controlling F toxicity at the low pH value, provided the concentration was no greater than 180 p.p.m. F.

Analyses of the leaves for F are shown in table 7. On the loam, at the low pH value, the F content of the tomato leaves ranged from 23 p.p.m., where no F had been added, to 1,008 p.p.m., where 360 p.p.m. of the element had been applied. For the medium pH value, the range was 15 to 480 p.p.m. F; and at the high pH value, from 7 to 91 p.p.m. Where the rate of application of  $P_2O_5$  was doubled, these values were lowered appreciably in most cases, but most significantly at the low pH value. The F content of the leaves of the plants grown on the sandy loam showed the same trends as those of the plants on the loam.

TABLE 8

*Fluorine content of roots of tomato—crop II—grown on sandy loam under different fluorine treatments*

$P_2O_5$	F ADDED	FLUORINE CONTENT OF ROOTS		
		pH 6.3	pH 5.5	pH 4.5
<i>lb./A.</i>	<i>p. p. m.</i>	<i>p. p. m.</i>	<i>p. p. m.</i>	<i>p. p. m.</i>
200	0	26	20	22
	90	38	148	180
	180	82	386	—
	360	560	—	—
400	0	21	14	20
	90	32	64	120
	180	42	82	—
	360	363	—	—

At the end of this experiment root samples were obtained from as many of the various HF treatments as possible. The analyses (table 8) indicate that the F content of tomato roots without HF treatment averaged about 20 p.p.m. The F content of the roots increased with F applications, but was reduced where increasing amounts of lime had been used. At the low pH value, it was well over 100 p.p.m., with as little as 90 p.p.m. F applied to the soil. At the high pH value, it was lowered to less than 40 p.p.m. Doubling the application of  $P_2O_5$  resulted in a still greater reduction in F content. Comparison of the F content of the roots with that of the leaves (table 7) shows that, under similar F treatments, the roots were generally higher in F.

#### SUMMARY AND CONCLUSIONS

Four series of studies with Sassafras sandy loam and loam soils were carried out to determine the concentration at which F becomes toxic to buckwheat and tomato plants. Corrective measures were studied for overcoming the toxic effects of high F concentrations in these soils.

With buckwheat, additions up to 180 p.p.m. F as NaF did not injure the plants at pH values of 5.5 or above. Fluorine at 360 p.p.m. was injurious on the loam, even at pH 6.5. Toxicity, as reflected in yields, was reduced by increasing the rate of application of  $P_2O_5$ , especially at low pH values.

Large increases in the F content of buckwheat plants were obtained on soils at a pH value of 4.5 from the use of 180 and 360 p.p.m. F. When the pH value of the soil was raised to 5.5 by the use of lime, the plants contained only one sixth to one seventh as much of the element. At pH 6.5, the F content was reduced to a relatively low point. Doubling the rate of application of  $P_2O_5$  resulted in a reduction in the F content in some cases, but not consistently.

With tomato plants, injury occurred at 360 p.p.m. F on the sandy loam at a pH value of 6.5. On the loam, the toxic point was between 360 and 720 p.p.m. F. At lower pH values, toxicity was much more pronounced on both soils.

The point at which dilute HF solutions, applied to the surface of the soils, produced toxicity symptoms and impaired growth of tomato plants was similar to that resulting from the use of the same quantity of F as NaF, but the injury was aggravated. Soils receiving the higher lime and phosphate treatments withstood the HF best.

Toxicity symptoms appeared first as a curling and wilting of the leaves, with spotted, chlorotic areas between the veins. The edges of the leaves showed a burning or browning effect that progressed inward as a gradual necrosis.

On the loam, toxic effects from added F, up to a concentration of 180 p.p.m. F, were almost completely prevented by the use of lime, and fairly effective control was obtained even at 360 p.p.m. Above that concentration, yields fell off rapidly. On the sandy loam, toxicity from 180 p.p.m. F was effectively prevented by liming to pH 6.5, but yields fell off markedly above that F level. Doubling the rate of application of  $P_2O_5$  proved most effective in preventing F toxicity at low pH values, provided the F concentration was no greater than 180 p.p.m.

Analyses of tomato leaves grown at low lime levels ranged from 23 p.p.m., where no F was used, to 1,008 p.p.m., where 360 p.p.m. F had been added. At the intermediate pH level the range was from 15 to 480 p.p.m. F; and at the highest pH level, from 7 to 91 p.p.m.

The F content of tomato roots increased in proportion to the F concentrations in the soil, but it was reduced wherever lime or phosphate was applied. For similar F treatments, however, the roots were generally higher in F than the leaves.

Injurious effects from comparable F treatments were of much greater severity on sandy loam than on loam.

The point at which F became toxic varied with the type of soil, its lime and phosphate levels, and the type of plant grown.





# CORRELATION OF MICROBIOLOGICAL AND CHEMICAL SOIL DATA WITH CROP YIELDS OF THE JORDAN SOIL FERTILITY PLOTS<sup>1</sup>

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Studies in soil microbiology have served to emphasize the important role played by microorganisms in the development and maintenance of soil fertility. Through the use of improved laboratory technique and the introduction of standard methods of procedure, more concordant results have been obtained and these have led to the conclusion that the activities of the soil microorganisms may serve as an index of fertility.

Burgess (2) concluded that nitrification (soil-culture method) is by far the most accurate biological soil test yet perfected for predicting probable fertility. Gainey (3) asserted that it is not unreasonable to find a correlation existing between the nitrifying capacity of a soil and its ability to support vigorous plant growth.

Waksman (10), Kelley (5), and Waksman and Starkey (11) emphasized the fact that addition of lime to acid soils results in an increase in number and activities of soil bacteria. Kelley (5) concluded that the influence of soil reaction upon nitrification can account for many results in which a lack of correlation between nitrification and soil productivity has been reported.

Waksman and Heukelekian (12) credited Christensen as the first to suggest that the power of the soil to decompose cellulose may serve as an index of fertility. These authors concluded that the cellulose-decomposing power of the soil, both with and without additions of small amounts of available nitrogen, can yield information for the differentiation of levels of soil fertility.

Andrews (1) reported that the findings of Holben (4) indicated that the use of cellulose as a source of energy material for soil microorganisms was not entirely satisfactory. Andrews failed to note, however, that these cellulose studies were made on the plot soils of tier I of the Jordan Soil Fertility Experiments where no lime had been applied since 1881 except on three of the 36 plots and where the pH of the plot soils varied from 7.8 to 4.0. He reported results which showed a relationship between the response of soil microorganisms and crop plants to nitrogen and phosphorus, measured in terms of CO<sub>2</sub> recovered from the decomposition of added mannitol.

Prince (7) concluded from a study of three plots of the New Jersey Station that a correlation was found between their relative fertility and the amounts of total and nitrate nitrogen present.

<sup>1</sup> Contribution from the department of agronomy, The Pennsylvania State College, School of Agriculture and Experiment Station, State College, Pennsylvania. Authorized for publication on May 26, 1948, as paper No. 1445 in the Journal Series of the Pennsylvania School of Agriculture.

Many papers dealing with soil factors in relation to fertility show that correlations reported to have been established were based on small numbers or on conclusions unsupported by statistical analysis. The term "correlation" has been applied too frequently to a casual relationship and not in terms of correlation coefficients.

The Jordan Soil Fertility Experiments of the Pennsylvania Station (6) offered an unparalleled opportunity for a more extensive and comprehensive study of the relationships between microbiological activity and chemical data and the relative fertility of the differently treated plots soils. This is especially true of the 36 plot soils of tier 4, where lime has been applied at frequent intervals since 1922 and where soil acidity is not a limiting factor.

#### EXPERIMENTAL MATERIALS AND METHODS

The biological and chemical soil data presented are based on results of a study of the 36 plot soils of tier 4 of the Jordan series, sampled in 1931 and 1935 at the end of 50 and 54 years of continuous cropping. The soils were sampled in fall after the harvest of corn.

Each correlation presented is expressed in terms of Pearce product-moment correlation coefficients. The 77 correlation coefficients included are from the data of 36 plots. The microbiological activity of the soils is measured in terms of cellulose-decomposing power, residual-soil-organic-matter-decomposing power (soil respiration), and nitrifying capacity. The first two include both the 1931 and 1935 samples, and the last includes only samples collected in 1931.

The crop yields used in the correlation studies include each corn crop (grain yields), the sum of the two corn crops, and the sum of the preceding yields of hay, wheat, and oats (grain).

The cellulose-decomposing power is based on the  $\text{CO}_2$  recovered at the end of 7- and 14-day incubation periods. The data on nitrifying capacity are based on nitrate-nitrogen recovered in the soils at the end of incubation periods of 21, 30, 42, 60, and 74 days.

The chemical soil data, correlated with crop yields, include residual  $\text{NO}_3\text{-N}$ , available P, exchangeable K, inorganic water-soluble salts, total soil nitrogen, and organic carbon.

Cellulose-decomposing power of the plot soils was determined as described in a previous paper (17), except that no nitrogen was added and that hot phosphoric acid was introduced into the flasks at the end of the 14-day incubation period as a means of recovering the  $\text{CO}_2$  from carbonates.

The nitrifying capacity of each plot soil was determined by incubation at room temperature for 74 days, during which time samples were removed at intervals of 21, 30, 42, 60, and 74 days. Throughout the entire incubation period each of the 36 plot soils was maintained at a moisture content equivalent to 55 per cent of the maximum water-holding capacity. Nitrate-nitrogen was determined in the water extract by reduction with Devarda's alloy and distillation of the ammonia into standard acid.

Readily available P was determined by the Truog method (8), exchangeable

K by the method of Volk and Truog (9), organic carbon by the White and Holben method (13, 18), and total soil nitrogen by the official A.O.A.C. procedure. Inorganic water-soluble salts were determined by shaking 100 gm. of air-dried soil with 500 ml. of distilled water, refiltering until the filtrate was clear, treating the evaporated residue with hydrogen peroxide and a drop of ammonia, and then drying at 100°C. to constant weights.

RESULTS OF STATISTICAL ANALYSIS<sup>2</sup>*Microbiological activities*

*Cellulose-decomposing power.* Soil and crop data which deal with the correlations of the cellulose-decomposing power of the 36 plot soils are shown in table 1. Regardless of the period of incubation and correlations of crops used, the cellu-

TABLE 1  
*Correlation coefficients (r) of cellulose-decomposing power with crop yields*

INCUBATION PERIOD	NATURE OF CROPS	r
<i>days</i>		
14	Corn grain, 1931	.79**
14	Corn grain, 1935	.79**
14	Sum of corn grain	.87**
14	Sum of four crops, 1928-1931	.85**
14	Sum of four crops, 1932-1935	.89**
14	Sum of eight crops	.90**
7	Corn grain, 1931	.87**
7	Corn grain, 1935	.83**
7	Sum of corn grain	.93**
7	Sum of four crops, 1928-1931	.93**
7	Sum of four crops, 1932-1935	.89**
7	Sum of eight crops	.92**

\*\* Significant beyond 1 per cent level (99:1).

lose-decomposing power of the soils shows correlations with crop yields which are highly significant beyond the 1 per cent level (99:1).

The data of table 2, based on the total CO<sub>2</sub> recovered from the cellulose-treated soils (soil and cellulose), show correlations with crop yields which are also highly significant well beyond the 1 per cent level.

*Soil-organic-matter-decomposing power (soil respirations).* Correlations of the organic-matter-decomposing power of the plot soils (soil respirations) are included in table 3. The correlations found to exist between soil respiration and crop yields, though significant beyond the 1 per cent level, show correlation coefficients which are definitely at a lower level than those obtained for the cellulose-decomposing power of the plot soils.

<sup>2</sup> Correlation coefficients were computed by Mildred D. John, assistant in agronomy, in charge of statistical analysis, hybrid-corn program, to whom the authors express their appreciation.

TABLE 2

*Correlation coefficients (r) of cellulose- and organic-matter-decomposing power with crop yields*

INCUBATION PERIOD	NATURE OF CROPS	
<i>days</i>		
14	Corn grain, 1931	.80**
14	Corn grain, 1935	.81**
14	Sum of corn grain	.89**
14	Sum of four crops, 1928-1931	.85**
14	Sum of four crops, 1932-1935	.88**
14	Sum of eight crops	.97**
7	Corn grain, 1931	.87**
7	Corn grain, 1935	.83**
7	Sum of corn grain	.94**
7	Sum of four crops, 1928-1931	.88**
7	Sum of four crops, 1932-1935	.89**
7	Sum of eight crops	.95**

\*\* Significant beyond 1 per cent level (99:1).

TABLE 3

*Correlations coefficients (r) of soil-organic-matter-decomposing power (soil respiration) with crop yields*

INCUBATION PERIOD	NATURE OF CROPS	
<i>days</i>		
14	Corn grain, 1931	.72**
14	Corn grain, 1935	.60**
14	Sum of corn grain	.76**
14	Sum of four crops, 1928-1931	.78**
14	Sum of four crops, 1932-1935	.76**
14	Sum of eight crops	.79**

\*\* Significant beyond 1 per cent level (99:1).

TABLE 4

*Correlation coefficients (r) of nitrifying capacity with crop yields*

INCUBATION PERIOD	NATURE OF CROPS	
<i>days</i>		
21	Corn grain, 1931	.68**
30	Corn grain, 1931	.73**
42	Corn grain, 1931	.74**
60	Corn grain, 1931	.71**
74	Corn grain, 1931	.81**
21	Sum of four crops, 1928-1931	.67**
30	Sum of four crops, 1928-1931	.73**
42	Sum of four crops, 1928-1931	.73**
60	Sum of four crops, 1928-1931	.70**
74	Sum of four crops, 1928-1931	.83**

\*\* Significant beyond 1 per cent level (99:1).

*Nitrifying capacity.* Correlations of the nitrifying capacity of the plot soils with crop yields are shown in table 4. In relation to each of the five incubation periods, highly significant correlations beyond the 1 per cent level exist between the nitrifying capacity of the plot soils and yields of the several crops.

Tables 1 to 4 show conclusively that highly significant correlations exist between the activities of soil microorganisms and crop yields as measured by the cellulose-decomposing power and nitrifying capacity of the 36 plot soils. These

TABLE 5  
*Correlation coefficients (r) of soil nutrients with crop yields*

SOIL NUTRIENTS	NATURE OF CROPS	
NO <sub>3</sub> -N, 1931	Corn grain, 1931	.40*
NO <sub>3</sub> -N, 1935	Corn grain, 1935	.57**
NO <sub>3</sub> -N, 1931	Sum of four crops, 1928-1931	.42*
NO <sub>3</sub> -N, 1935	Sum of four crops, 1932-1935	.60**
NO <sub>3</sub> -N, 1931, 1935	Sum of eight crops	.40*
Available P, 1931	Corn grain, 1931	.61**
Available P, 1935	Corn grain, 1935	.62**
Available P, 1931	Sum of four crops, 1928-1931	.67**
Available P, 1935	Sum of four crops, 1932-1935	.56**
Available P, 1931, 1935	Sum of eight crops	.63**
Exchangeable K, 1935	Corn grain, 1935	.25
Exchangeable K, 1935	Sum of four crops, 1932-1935	.30
P + K, 1935	Corn grain, 1935	.40*
P + K, 1935	Sum of four crops, 1932-1935	.43**
P + N, 1931	Corn grain, 1931	.50**
P + N, 1935	Corn grain, 1935	.70**
P + N, 1931	Sum of four crops, 1928-1931	.49**
P + N, 1935	Sum of four crops, 1932-1935	.64**
P + N, 1931, 1935	Sum of eight crops	.60**
N + K, 1935	Corn grain, 1935	.14
N + K, 1935	Sum of four crops, 1932-1935	.19
N + P + K, 1935	Corn grain, 1935	.39*
N + P + K, 1935	Sum of four crops, 1932-1935	.42**
Water-soluble salts, 1935	Corn grain, 1935	.19
Water-soluble salts, 1935	Sum of four crops, 1932-1935	.12

\* Significant beyond 5 per cent level (19:1).

\*\* Significant beyond 1 per cent level (99:1).

data fully substantiate the reports of previous investigations pertaining to the significance of microbiological activity as a measure of fertility.

#### *Chemical soil data*

Correlations established between several chemical soil constituents and crop yields are shown in tables 5 and 6. Available P based on both the 1931 and 1935 samples shows a significant correlation with crop yields beyond the 1 per cent level. The residual nitrate-nitrogen (NO<sub>3</sub>-N), based on the 1935 samples, shows a significant correlation with crop yields beyond the 1 per cent level, and, based on the 1931 samples, a significant correlation beyond the 5 per cent level (19:1).

The sum of available P and  $\text{NO}_3\text{-N}$ , designated as P + N, 1935 samples, shows the highest correlations of all the chemical data with crop yields beyond the 1 per cent level. Exchangeable K and the inorganic water-soluble salts show no significant correlation with crop yields. These data are in accord with the results obtained by Andrews (1) in his study of cotton soils.

Both total soil nitrogen and organic carbon (table 6), each a measure of residual soil organic matter, show highly significant correlations with crop yields beyond the 1 per cent level. These highly significant correlation coefficients serve to emphasize further the importance of soil organic matter as an index of fertility, established by the authors (14, 15, 16) and other investigators.

TABLE 6

*Correlation coefficients (r) of total soil nitrogen (N) and organic carbon (C) with crop yields*

SOIL CONSTITUENTS	NATURE OF CROPS	r
N, 1931	Corn grain, 1931	.79**
N, 1935	Corn grain, 1935	.78**
N, 1931, 1935	Sum of corn grain	.87**
N, 1931	Sum of four crops, 1928-1931	.85**
N, 1935	Sum of four crops, 1932-1935	.89**
N, 1931, 1935	Sum of eight crops	.90**
C, 1931	Corn grain, 1931	.87**
C, 1935	Corn grain, 1935	.83**
C, 1931, 1935	Sum of corn grain	.93**
C, 1931	Sum of four crops, 1928-1931	.93**
C, 1935	Sum of four crops, 1932-1935	.89**
C, 1931, 1935	Sum of eight crops	.92**

\*\* Significant beyond 1 per cent level (99:1).

#### SUMMARY

Correlations of microbiological and chemical soil data with crop yields are expressed in terms of Pearson product-moment correlation coefficients. The results are based on 36 soil samples collected from each plot of tier 4 of the Jordan Series. The soil samples were taken after corn harvest at the end of 50 and 54 years of continuous cropping.

Highly significant correlations beyond the 1 per cent level were found to exist between crop yields and microbiological activity of the 36 plot soils as measured by the cellulose-decomposing power and nitrifying capacity.

Total soil nitrogen and organic carbon, each a measure of residual soil organic matter, showed highly significant correlations with crop yields beyond the 1 per cent level. The correlation coefficients obtained were comparable with those obtained for microbiological activity.

Readily available P and  $\text{NO}_3\text{-N}$  (1935 samples) showed significant correlations with crop yields beyond the 1 per cent level.

No significant correlations were found to exist between crop yields and exchangeable K and inorganic water-soluble salts.

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# A COMPARISON OF OLIVINE, SERPENTINE, MAGNESITE, DOLOMITE, AND SELECTIVELY CALCINED DOLOMITE AS SOURCES OF MAGNESIUM FOR RED CLOVER<sup>1</sup>

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Magnesium fertilization now is deemed a primary requirement for plant growth on the soils of extensive humid regions (5, 30), and for certain crops in particular (7). In certain sections of the Coastal Plains dolomitic limestone has been incorporated directly as a means of supplying that requirement. The fertilizer industry has sought to provide nutrient magnesium through inclusions of dolomite, calcined kieserite, selectively calcined dolomite, or the oxide as such and as hydrated dolomitic lime (25, 26). Because of a scarcity of the carbonate mineral in New Zealand, serpentine has been utilized there in lieu of dolomite for conditioning superphosphate (1, 2).

In studies reported from this Station in 1914, the mineral silicates of calcium and magnesium proved more beneficial than the corresponding carbonates on the growth of red clover in pot cultures grown outdoors (13). Further consideration of utilization of mineral silicates of magnesium to provide that essential element to plants was prompted by the illustrated report on the geological survey conducted by the North Carolina Department of Conservation and Development, in collaboration with the Tennessee Valley Authority (11). Extensive occurrences of forsterite olivine and serpentine were located in formations easily accessible at many points in Western North Carolina and in North Georgia. Because of those findings, and of correspondence with New Zealand advocates of the utilization of serpentine as a conditioning material for superphosphate, the reactivities of the forsterite minerals and other magnesian materials were compared through analytical studies of their respective mixtures with concentrated superphosphate. Analyses of those mixtures revealed that the phosphate transitions induced by olivine, raw serpentine, and calcined serpentine exceeded the transitions induced by equivalent quantities of dolomite and of magnesite (9, 24). Those mixtures have been compared as to their fertilizer effectiveness through pot cultures studies that will be reported. The chemical evaluations of the respective mixtures were made by means of an analytical procedure that was developed for determining the engendered dimagnesium phosphate (10).

Since the magnesium content of the forsterite minerals was nearly thrice the incidence of that element in the widely used Knox dolomite, and because of the magnitude of the located formations of easily accessible and cheaply mined silicates of magnesium, it seemed desirable to ascertain whether the direct incorporation of those magnesian minerals could be depended upon to supply magnesium to crops on soils that are not needful of additions of calcium. The present findings stem from pot culture studies of that possibility.

<sup>1</sup> Conducted in collaboration with The Tennessee Valley Authority.

## MATERIALS AND METHODS

The intent was to compare incorporations of olivine and serpentine to equivalent inputs of magnesite, basic magnesium carbonate, dolomite, and selectively calcined dolomite (SCD) as immediate sources of nutrient magnesium for red clover grown on Hartsells fine sandy loam and on Clarksville silt loam in pot cultures in the greenhouse.

TABLE 1  
*Partial analysis of liming materials incorporated in soils*

LABORATORY NUMBER	LIMING MATERIAL	CaO	MgO	CaCO <sub>3</sub> - EQUIV- ALENCE
		<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
S-1216	Limestone (Appalachian marble)	53.5	1.0	98.0
S-1241	Calcite	56.0	0.0	100.0
S-1242	Magnesite	1.5	45.2	112.2
S-1252	Precipitated MgCO <sub>3</sub> , heavy	0.7	40.5	101.0
S-1253	Ppt. MgCO <sub>3</sub> (S-1252), calcined at 900°C.	1.7	96.0	241.3
S-1254	Ppt. MgCO <sub>3</sub> (S-1252), calcined at 450°C.	1.7	91.4	230.0
S-1250	Dolomite, West Virginia	29.1	21.6	105.5
S-32	Dolomite, Knox formation, Tennessee	27.4	17.9	93.4
P-608	Selectively calcined dolomite*	39.5	28.0	140.0
—	C.p. CaCO <sub>3</sub> -MgO (S-1254) mixture†	28.0	20.1	*
—	CaO from CaCO <sub>3</sub> -MgO (S-1254)‡	28.0	20.1	†
S-1027	Wollastonite, raw	45.9	Trace	82.0
S-1027	Wollastonite, calcined	45.9	Trace	82.0
S-1027	Wollastonite, fused and quenched	45.9	Trace	82.0
S-1239	Serpentine, raw	0.56	38.9	97.6
S-1239	Serpentine, calcined	0.34	43.6	108.2
S-1239	Serpentine, fused and quenched	0.45	43.2	108.0
S-996	Olivine, raw	1.34	49.4	125.0
S-996	Olivine, calcined	0.17	50.5	125.6
S-996	Olivine, fused and quenched	0.22	49.9	124.3

\* Comprised CaCO<sub>3</sub>-MgO.

† Half of the CaCO<sub>3</sub>-equivalence was from CaCO<sub>3</sub> and half from MgO.

‡ Half of the CaCO<sub>3</sub>-equivalence was from CaO and half from MgO.

The acidic Hartsells soil was known to be responsive to liming at fairly heavy rates, and to dolomite in particular, whereas the Clarksville soil had a light liming requirement.

The liming materials, which had been screened through a 100-mesh sieve, were incorporated full-depth in the soil, at 3-ton CaCO<sub>3</sub>-equivalence on the Hartsells soil and at 1½-ton equivalence on the Clarksville. Partial analyses of the liming materials used are given in table 1. Wilson Dam superphosphate, to supply

80 pounds  $P_2O_5$  (as stipulated in tables 2, 3, 4), and  $K_2SO_4$ , to supply 185 pounds, were mixed into the upper 4-inch half of the soil. All materials were incorporated simultaneously at acre-surface rates just prior to the seeding of red clover. Two cuttings of the clover were obtained.

## RESULTS

### *Hartsells soil*

Findings for dry weight and percentage content of  $P_2O_5$ , calcium, and magnesium in the first crop of red clover, uptake of nutrients by the crop, and pH values of the soil are given for the fine sandy loam in table 2. Representative responses by the red clover are illustrated in figure 1. Small yields of 1 to 4 gm. were induced by the several liming materials, and the superphosphate induced a yield of 7.2 gm., when the respective materials were used alone. Hence, consideration of the effects of the liming materials upon crop response and composition is confined to their joint incorporations with superphosphate, unless otherwise stated.

Limestone, wollastonite, the dolomites, selectively calcined dolomite, and the corresponding mixtures of  $CaCO_3$  and  $MgO$  induced the largest yields, 18.5 to 23.5 gm., whereas calcite and magnesite caused respective yields of 17.2 and 16.4 gm. Olivine and raw serpentine induced smaller yields of from 10.0 to 11.0 gm., whereas the smallest increases, 5.0 to 8.0 gm., came from basic magnesium carbonate and its calcines.

The yield responses by red clover (a) served to indicate those combinations that supplied the major essentials for promotion of growth, (b) served to register the inertness of the incorporated serpentine and olivine, and (c) demonstrated that the highly dissolvable basic magnesium carbonate and its calcines caused an unbalance in the early supply of nutrients in the soil systems. The inertness of the mineral silicates was reflected also by their relatively slight effects upon pH values and by a yellowing of the leaves. The growth repression induced by the basic carbonate and its oxide can be attributed to their ready dissolubility, which induced high alkalinity initially and a resultant repression in the uptake of calcium. After the second crop of red clover, however, the soil that received the carbonate, or its oxide, showed lessened alkalinity. The decrease in pH is in accord with, and is elucidated through, earlier findings, which showed that although the heavy incorporations of the basic carbonate induced sterility, the induced toxicity disappeared after the sorbed magnesium had undergone "aging" (14, 15, 16). Moreover, the toxic effect induced by heavy incorporations of magnesium oxide was corrected through simultaneous incorporations of silicic acid (19).

It has been established that wide variations in plant composition can be induced through variance in the proportions of bases introduced into the soil, and yet maximal growth still may obtain (3, 6, 8, 12, 27, 28, 29). This fact is demonstrated through the composition of the initial crop of red clover from the Hartsells soil in the present experiment. In general, the phosphorus content of the red clover was fairly uniform for the joint incorporations of superphosphate and

TABLE 2

*Influence of incorporations of limestone, dolomite, magnesite, serpentine, and olivine plus superphosphate into Hartsells fine sandy loam, as registered by response and composition of red clover (first cutting)*

SOIL TREATMENT			CROP							pH OF SOIL
Liming material*	P <sub>2</sub> O <sub>5</sub> †	Dry weight	P <sub>2</sub> O <sub>5</sub>		Ca		Mg			
			Content	Uptake	Content	Uptake	Content	Uptake		
			lb./A.	gm.	per cent	lb./A.	per cent	lb./A.	per cent	
None.....	0	1.3	0.30	1	1.63	5	0.30	1	4.9	
None.....	80	7.2	0.34	6	1.76	32	0.30	6	4.9	
Limestone.....	0	2.2	0.30	2	2.53	14	0.21	1	6.4	
Limestone.....	80	18.5	0.26	12	2.76	128	0.18	8	6.5	
Limestone, plus MgSO <sub>4</sub> .....	80	20.1	0.30	15	2.50	126	0.28	14	6.6	
Calcite.....	80	17.2	0.30	13	2.68	115	0.13	6	6.2	
Magnesite.....	0	3.1	0.29	2	1.20	9	0.86	7	5.7	
Magnesite.....	80	16.4	0.25	10	1.32	54	0.72	30	5.7	
MgCO <sub>3</sub> ‡.....	80	7.8	0.44	9	0.57	11	1.33	26	6.5	
MgCO <sub>3</sub> , calcined 450°C.....	80	6.2	0.53	8	0.53	8	1.48	23	6.6	
MgCO <sub>3</sub> , calcined 900°C.....	80	7.5	0.49	9	0.55	10	1.36	26	6.5	
Dolomite, W. Va.....	0	3.4	0.33	3	1.95	17	0.67	6	6.4	
Dolomite, W. Va.....	80	23.5	0.26	15	1.89	111	0.61	36	6.4	
Dolomite, Knox.....	0	4.5	0.31	4	1.97	22	0.67	8	6.5	
Dolomite, Knox.....	80	21.6	0.27	15	2.16	117	0.65	35	6.7	
SCD§.....	80	22.0	0.29	16	2.04	112	0.65	36	6.5	
CaCO <sub>3</sub> + MgO mixture.....	80	23.0	0.32	19	2.08	120	0.66	38	6.5	
CaO + MgO mixture.....	80	22.5	0.30	17	2.14	121	0.68	38	6.3	
Wollastonite, raw.....	0	4.3	0.27	3	2.58	28	0.30	3	6.2	
Wollastonite, raw.....	80	20.4	0.27	14	2.60	133	0.21	11	6.1	
Wollastonite, calcined.....	80	22.0	0.27	15	2.56	141	0.19	11	6.2	
Wollastonite, f & q¶.....	80	21.3	0.25	13	2.50	133	0.17	9	6.1	
Serpentine, raw.....	0	1.1	0.27	1	1.66	5	0.39	1	5.0	
Serpentine, raw.....	80	10.4	0.29	8	1.65	43	0.38	10	5.1	
Serpentine, calcined.....	80	11.8	0.27	8	1.47	44	0.53	16	5.1	
Serpentine, f & q.....	80	12.3	0.27	8	1.57	48	0.52	16	5.0	
Olivine, raw.....	0	1.6	0.25	1	1.46	6	0.53	2	5.2	
Olivine, raw.....	80	11.2	0.27	8	1.50	42	0.51	14	5.2	
Olivine, calcined.....	80	11.6	0.29	9	1.46	42	0.49	15	5.3	
Olivine, f & q.....	80	10.2	0.27	7	1.49	38	0.49	13	5.2	

\* At rate of 3 tons CaCO<sub>3</sub>-equivalence per acre surface. Details concerning materials are given in table 1.

† As Wilson Dam superphosphate.

‡ The "heavy" precipitated "basic" carbonate.

§ Selectively calcined dolomite (CaCO<sub>3</sub>-MgO).

¶ f & q = fused and quenched.





the several magnesian materials, although the precipitated carbonate and its calcines induced maximal percentage content of the small crop response to those materials. Apparently, no significant increases in the content and uptake of phosphorus were induced by the magnesium that was carried by the raw dolomites and other magnesian minerals.

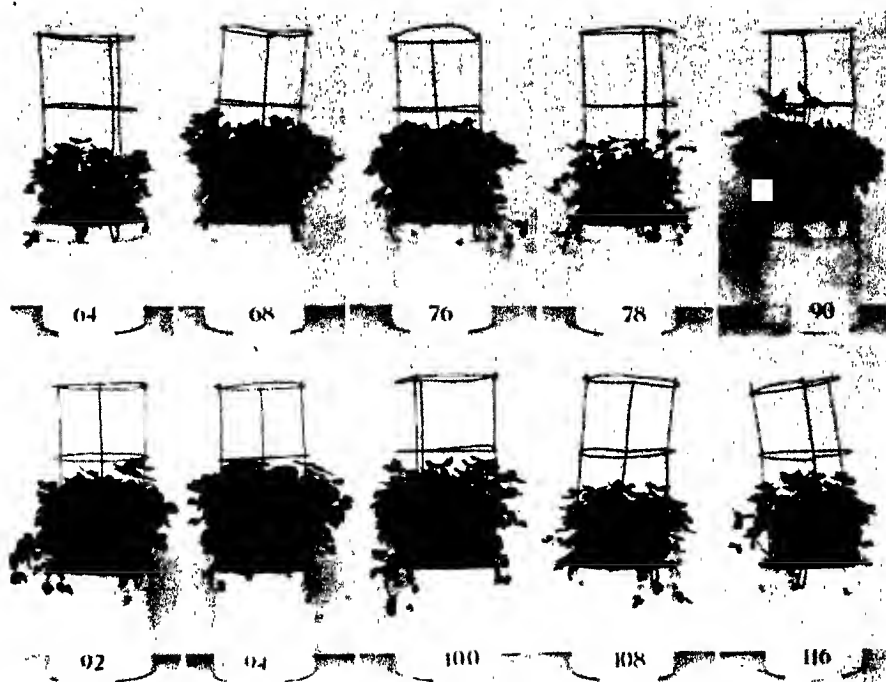


FIG. 1. GROWTH OF RED CLOVER INDUCED THROUGH INCORPORATIONS OF DIFFERENT MAGNESIC MATERIALS INTO HARTSELLS FINE SANDY LOAM

64, none; 68, limestone; 76, magnesite; 78, basic Mg carbonate; 90, dolomite; 92, selectively calcined dolomite; 94,  $\text{CaCO}_3 + \text{MgO}$ ; 100, wollastonite; 108, serpentine; 116, olivine.

The magnesian materials were incorporated full-depth at rate of 3 tons  $\text{CaCO}_3$ -equivalence. All cultures received upper-half incorporations of concentrated superphosphate at rate of 80 pounds of  $\text{P}_2\text{O}_5$  per acre surface.

The usual effects of "reciprocal repression" induced by incorporations of the more dissolvable basic forms of calcium and of magnesium (17, 18, 20), are reflected through the proportions of those two elements in the red clover. The upper range for calcium content—2.50 or 2.76 per cent—and the lower range for magnesium content—0.13 to 0.30 per cent—were induced by high calcic limestone, by calcite, and by wollastonite. The distinctive behavior and the liming effectiveness of wollastonite were revealed in related experiments (17, 20, 21, 22, 23). In contrast, low range for calcium content—0.53 to 0.57 per cent—and high range for magnesium content—1.33 to 1.48 per cent—were induced by the precipitated basic magnesium carbonate and its calcines; whereas, as already noted,

the small growth resultant from the incorporations of these highly alkaline materials is attributed to the unbalancing of normal Ca-Mg relationships.

Intermediate proportions in calcium and magnesium occurrence in the clover were induced by magnesite, by the dolomites, and by the other materials that comprised calcium and magnesium in dolomitic ratio. Since the red clover gave minor responses to the relatively inert serpentine and olivine, proportionate plant content of calcium and magnesium was not altered materially. The magnesium content derived from the raw serpentine was 0.38 per cent less than that derived from the calcined serpentine, or from the fused and quenched serpentine, and was also less than the content from the raw, calcined, or fused and quenched olivine. In related studies (24) it had been found that the calcination of the hydrated serpentine effected some increase in reactivity and resulted in its conversion to olivine; that is, the calcine of the serpentine acquired an x-ray pattern identical to the pattern registered by olivine.

As noted, only the serpentine and olivine had failed to induce significant elevation in pH values. Such stability for the mineral silicates of magnesium in the soil systems is in contrast to the dissolubility in carbonated water (13) and to the ready decomposition of the magnesian minerals in their mixtures with superphosphate (9, 24).

Although carrying to the soil only about half as much magnesium as that carried by the serpentine and by the olivine, the dolomites imparted considerably higher content of magnesium to the red clover.

Responses by the second cuttings of red clover on the Hartsells soil are shown in table 4. Those materials that induced maximal responses by the initial crops, registered in like manner through the second cuttings. Although the precipitated basic carbonate of magnesium, and its calcines, still effected some depressions upon the second growth, these were less severe than those on the initial crop. Again, this is in accord with previously cited findings as to disappearance of the initial toxic effect after the magnesium of the incorporated basic carbonate had undergone "aging," and as to the corrective effect of the silicic acid supplements to the 4-ton incorporations of MgO (19). The ability of the additive silicic acid to correct magnesia-induced toxicity was reported also by Blanck, Melville, and Bocht in a more recent publication (4).

#### *Clarksville soil*

Dry weight, contents of  $P_2O_5$ , Ca, and Mg and their uptake by the first cutting of red clover, and induced changes in pH are given for the Clarksville soil in table 3, and dry weights for the second cutting are given in table 4.

Since superphosphate induced maximal growth of red clover on the unlimed soil, no distinction in effectiveness was registered by the several liming materials. The red clover showed less variance in composition than it did on the Hartsells soil. Highest incidence of magnesium was induced by the basic carbonate and its calcines, without attendant increase in the  $P_2O_5$  content; whereas the proportions of calcium and magnesium in the red clover varied according to the dolomitic incorporations. Intermediate content of magnesium was induced by



TABLE 3

*Influence of incorporations of limestone, dolomite, magnesite, serpentine, and olivine plus superphosphate into Clarksville silt loam, as registered by response and composition of red clover (first cutting)*

SOIL TREATMENT			CROP								pH OF SOIL
Liming material*	P <sub>2</sub> O <sub>5</sub> †	Dry weight	P <sub>2</sub> O <sub>5</sub>		Ca		Mg				
			Content Uptake		Content Uptake		Content Uptake				
			lb./A.	gm.	per cent	lb./A.	per cent	lb./A.	per cent	lb./A.	
None . . . . .	0	2.3	0.24	2	2.26	13	0.30	2	5.4		
None . . . . .	80	19.1	0.24	12	2.40	117	0.28	13	5.0		
Limestone . . . . .	0	2.6	0.32	2	2.34	15	0.26	2	6.7		
Limestone . . . . .	80	22.4	0.25	14	2.60	146	0.26	15	6.5		
Limestone plus MgSO <sub>4</sub> . . . . .	80	22.4	0.30	17	2.73	153	0.34	19	6.4		
Calcite . . . . .	80	20.5	0.27	14	2.84	146	0.28	14	6.2		
Magnesite . . . . .	0	1.8	0.27	1	1.80	8	0.48	2	6.0		
Magnesite . . . . .	80	19.6	0.25	12	2.15	105	0.47	23	5.9		
Carbonate, MgCO <sub>3</sub> ‡ . . . . .	80	19.6	0.33	16	1.50	74	0.85	42	6.5		
Carbonate, calcined 450°C. . . . .	80	19.5	0.30	15	1.66	81	0.84	41	6.7		
Carbonate, calcined 900°C. . . . .	80	21.7	0.27	15	1.47	80	0.84	46	6.6		
Dolomite, W. Va. . . . .	0	1.9	0.30	2	1.66	8	0.49	2	6.7		
Dolomite, W. Va. . . . .	80	19.4	0.25	12	2.13	103	0.49	24	6.6		
Dolomite, Knox . . . . .	0	2.0	0.30	2	1.70	9	0.47	2	6.6		
Dolomite, Knox . . . . .	80	19.6	0.29	14	2.23	110	0.49	24	6.8		
SCD§ . . . . .	80	21.3	0.29	16	1.98	106	0.54	29	6.6		
CaCO <sub>3</sub> + MgO mixture . . . . .	80	20.8	0.29	15	1.96	105	0.52	27	6.7		
CaO + MgO mixture . . . . .	80	22.0	0.24	13	2.12	117	0.54	30	6.4		
Wollastonite, raw . . . . .	0	2.6	0.29	2	2.18	17	0.40	3	6.4		
Wollastonite, raw . . . . .	80	21.7	0.27	15	2.64	143	0.31	17	6.4		
Wollastonite, calcined . . . . .	80	21.7	0.26	14	2.63	143	0.29	16	6.4		
Wollastonite, f & q¶ . . . . .	80	21.4	0.25	13	2.63	141	0.28	15	6.3		
Serpentine, raw . . . . .	0	1.8	0.25	1	1.91	9	0.34	2	5.2		
Serpentine, raw . . . . .	80	17.5	0.27	12	2.13	93	0.35	15	5.3		
Serpentine, calcined . . . . .	80	17.2	0.27	12	2.01	87	0.38	16	5.4		
Serpentine, f & q . . . . .	80	18.4	0.25	12	1.98	91	0.39	18	5.5		
Olivine, raw . . . . .	0	2.3	0.23	1	1.75	10	0.31	2	5.5		
Olivine, raw . . . . .	80	18.8	0.23	11	2.11	99	0.35	17	5.4		
Olivine, calcined . . . . .	80	18.8	0.25	12	2.16	102	0.35	17	5.4		
Olivine, f & q . . . . .	80	19.1	0.25	12	2.03	97	0.31	15	5.3		

\* At rate of 1½ tons CaCO<sub>3</sub>-equivalence per acre surface. Details concerning materials are given in table 1.

† As Wilson Dam superphosphate.

‡ The "heavy" precipitated "basic" carbonate.

§ Selectively calcined dolomite (CaCO<sub>3</sub>-MgO).

¶ f & q = fused and quenched.

TABLE 4

*Influence of incorporations of limestone, dolomite, magnesite, serpentine, and olivine plus superphosphate into the Hartsells and Clarksville soils, as registered by yield of red clover (second cutting)*

SOIL TREATMENT		DRY WEIGHT OF CLOVER	
Liming material*	P <sub>2</sub> O <sub>5</sub> †	Hartsells fine sandy loam	Clarksville silt loam
	lb./A.	gm.	gm.
None.....	0	1.1	1.8
None.....	80	2.8	6.9
Limestone.....	0	2.6	3.3
Limestone.....	80	9.6	9.1
Limestone plus MgSO <sub>4</sub> .....	80	9.3	11.1
Calcite.....	80	8.3	8.6
Magnesite.....	0	1.7	1.9
Magnesite.....	80	6.7	7.8
MgCO <sub>3</sub> ‡.....	80	6.3	8.1
MgCO <sub>3</sub> , calcined 450°C.....	80	5.6	6.8
MgCO <sub>3</sub> , calcined 900°C.....	80	7.0	7.4
Dolomite, W. Va....	0	2.6	2.3
Dolomite, W. Va....	80	9.5	7.9
Dolomite, Knox....	0	2.7	3.0
Dolomite, Knox....	80	9.2	10.6
SCD§.....	80	9.7	10.6
CaCO <sub>3</sub> + MgO mixture.....	80	10.2	11.1
CaO¶ + MgO mixture.....	80	10.9	8.9
Wollastonite, raw.....	0	2.5	3.0
Wollastonite, raw.....	80	8.4	10.4
Wollastonite, calcined.....	80	7.8	10.7
Wollastonite, f & q¶.....	80	10.8	9.9
Serpentine, raw.....	0	0.7	2.2
Serpentine, raw.....	80	3.6	8.0
Serpentine, calcined.....	80	2.4	7.3
Serpentine, f & q.....	80	4.7	8.6
Olivine, raw.....	0	0.8	1.7
Olivine, raw.....	80	3.3	9.1
Olivine, calcined.....	80	2.6	7.3
Olivine, f & q.....	80	2.0	9.5

\* At rates of 3 tons CaCO<sub>3</sub>-equivalence for Hartsells fine sandy loam and 1½ tons for Clarksville silt loam. Details concerning materials are given in table 1.

† Wilson Dam superphosphate.

‡ The "heavy" precipitated "basic" carbonate.

§ Selectively calcined dolomite CaCO<sub>3</sub>-MgO.

¶ f & q = fused and quenched.





the raw dolomite, by the mixtures that comprised calcium and magnesium in near-dolomitic proportion, and by magnesite. Incidence of magnesium from the input of olivine and of serpentine was only slightly higher than the content induced by the high calcic limestone and by wollastonite. When a preponderance of either calcium or magnesium was provided in the soil through the incorporations of their more dissolvable forms, the phenomena of "reciprocal repressions" were registered through plant content, as they had been through occurrence of the two elements in the direct leachings from soils that had received corresponding incorporations (17, 18, 20).

Replacements of exchangeable H in the Clarksville soil were registered by the elevations in pH values induced by the bases that were supplied through the respective inputs of limestone, calcite, wollastonite, precipitated magnesium carbonate and its calcines, the dolomites, selectively calcined dolomite, and corresponding mixtures of calcium and magnesium; whereas the serpentine and olivine incorporations did not induce appreciable changes in pH values.

#### OBSERVATIONS

The fact that the mineral silicates of magnesium did not promote growth of red clover in the present pot cultures, when those minerals were incorporated directly, is not necessarily in conflict with the earlier findings as to favorable response by red clover on other soils that had received the silicates at much heavier rates in outdoor cultures and without supplemental fertilizer elements (13). Since the pot cultures of the present experiment were conducted in the greenhouse and under ideal conditions, it seems improbable that corresponding supplemented incorporations of the mineral silicates of magnesium would prove effective in practice. It seems obvious that, at rational rates of incorporation, the raw minerals cannot be depended upon to effect significant pH changes quickly or to provide nutrient magnesium for immediate crops. It might be, however, that in time heavy incorporations of pulverized forsterites would provide adequate nutrient magnesium for field crops. A protracted prefatory period of "aging" of rational incorporations might induce an adequacy of magnesium in acidic soils needful of that element and not correspondingly deficient in calcium. Yet, even though an adequate enhancement in the supply of available magnesium might be imparted ultimately through such incorporations of the magnesian minerals, an unbalance in plant nutrients would be induced in soils of depleted calcium content. Hence, neither of these procedures is deemed a practical means of providing magnesium for crops, whereas magnesium fertilization can be effected immediately and economically when the magnesian silicates are utilized to engender dimagnesium phosphate in their mixtures with superphosphate of adequate moisture content (24).

#### SUMMARY AND CONCLUSION

Olivine, serpentine, magnesite, basic carbonate of magnesium, dolomite, selectively calcined dolomite (SCD), and a corresponding mixture of  $\text{CaCO}_3$  and  $\text{MgO}$  were compared (*a*) as sources of magnesium for immediate seedings of red

clover on two acidic soils, with and without needful simultaneous incorporations of concentrated superphosphate, and (b) as media to effect elevation in pH values. In conjunction with 80-pound inputs of  $P_2O_5$  as concentrated superphosphate, (a) limestone, calcite, and wollastonite promoted plant response and induced significant elevations in pH values; (b) dolomite, selectively calcined dolomite, and corresponding mixtures of  $CaCO_3$  and  $MgO$  proved efficacious as sources of nutrient magnesium and in correction of soil acidity; (c) magnesite served as a good source of nutrient magnesium, although it induced virtually no effect upon soil acidity.

It does not appear feasible, or even admissible, to utilize the magnesium silicate minerals for direct incorporation into acidic soils at economic rates, since such incorporations did not serve effectively as sources of magnesium for red clover, whereas these minerals can be utilized effectively to engender dimagnesium phosphate in their mixtures with superphosphate.

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# A FIELD METHOD FOR ANALYZING THE SALINITY PROBLEM ON IRRIGATED LANDS

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The salinity problem is common to nearly all irrigated lands in the western part of the United States, and much research has been done on the factors involved. Results from the work must, however, be correlated for field use in developing an efficient plan for conservation irrigation. The problem appears to have three major parts:

1. Salt tolerance of the crop to be grown.
2. Salinity of the irrigation water.
3. Physical properties of the soil which permit or prevent maintenance of a salinity balance for profitable production of crops.

The upper limit of salt concentration that permits satisfactory plant growth varies with the salt tolerance of the crop to be grown. The concentration of salts increases the osmotic tension of the soil solution and reduces the availability of moisture to the plant.

Salts having strong toxic effect usually represent a small portion of the total salts present in most waters used for irrigation. Some of the more common salts, however, have some toxic effects that are usually reflected in stunted crops and lowered yields.

Field observations of West Texas conditions, correlated with available research information, indicate that crops of weak tolerance cannot be grown when the soil solution at field capacity exceeds 2 per cent concentration. The limit for crops of medium tolerance seems to be 2.3 per cent; 2.7 per cent may be the limit for crops of strong tolerance. Production may be expected to increase as concentrations are reduced, other factors being in balance.

## PROPOSED METHOD

Much work has been done on analysis of irrigation waters, and procedures are well established to determine the amount and kind of salts present. This is necessary information and must be examined for: 1. Amount of harmful salts; 2. Percentage sodium (of total cations); 3. Presence of boron or other toxic elements.

It appears from field observations that salts of low solubility, such as magnesium carbonate, calcium carbonate, calcium bicarbonate, and calcium sulfate, need not be considered harmful. Therefore, although the total dissolved solids in the example (table 1) is 1830 p.p.m., only 1160 p.p.m. should be considered harmful salts.

The percentage of sodium is important because almost any time it exceeds 60

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per cent of the total cations there is strong possibility that (black) alkali will occur even in calcareous soils.

Boron in quantities as small as 0.5 p.p.m. is considered injurious, and as much as 2.0 p.p.m. may make irrigation water unusable. Observations on irrigated areas in Texas, however, indicate as many instances of boron deficiency as of excesses.

When the tolerance of the plants to be grown and the quality of the water to be used are known, the most important remaining factor is the soil and some of its

TABLE 1  
*Typical results of laboratory analysis of irrigation water*

	P.P.M.	COMBINING WEIGHT	P.P.M.
Total solids.....	1830		
Boron.....	0.24		
Calcium (Ca <sup>++</sup> ).....	170	20.0	8.5
Magnesium (Mg <sup>++</sup> ).....	63	12.2	5.2
Sodium (Na <sup>+</sup> ).....	332	23.0	14.4
Chloride (Cl <sup>-</sup> ).....	498	35.5	14.0
Sulfate (SO <sub>4</sub> <sup>-</sup> ).....	577	48.0	12.0
Carbonate (CO <sub>3</sub> <sup>-</sup> ).....	tr.	30.0	tr.
Bicarbonate (HCO <sub>3</sub> <sup>-</sup> ).....	142	61.0	2.3
Total ions*.....	1782		

PROBABLE SALTS	COMBINED EQUIVALENTS	P.P.M. (HARMFUL)
Sodium chloride.....	14.0	322 + 497 = 819
Sodium sulfate.....	0.4	9 + 19 = 28
Magnesium sulfate.....	5.2	63 + 250 = 313
		Total..... = 1160
Calcium sulfate.....	6.4	
Calcium bicarbonate.....	2.1	

$$\text{Per cent sodium} = \frac{\text{Na} \times 100}{\text{Ca} + \text{Mg} + \text{Na} + \text{K}} = \frac{14.4 \times 100}{8.5 + 5.2 + 14.4} = \frac{1440}{28.1} = 51$$

\* Potassium (K<sup>+</sup>) and nitrate (NO<sub>3</sub><sup>-</sup>) ions not present in sample.

properties. Of these properties, two are significant when the soil is to be irrigated: 1. Field capacity—how much water the soil will hold against gravitational pull; 2. Permeability—how fast water (or air) will move through the soil. If field capacity of the soil is known, as well as the concentration of salt that the plant to be grown will tolerate, the limit of tolerance for the soil may be calculated as follows: *Percentage of field capacity times percentage of concentration plant will tolerate equals percentage of soil salinity plant will tolerate.*

For example, on a soil with a 30 per cent field capacity, a plant of medium salt tolerance (2.3 per cent) will have a limit of tolerance of 69 per cent (30 × 2.3) in soil salinity. (See left hand side of figure 1 for graphic solution.)

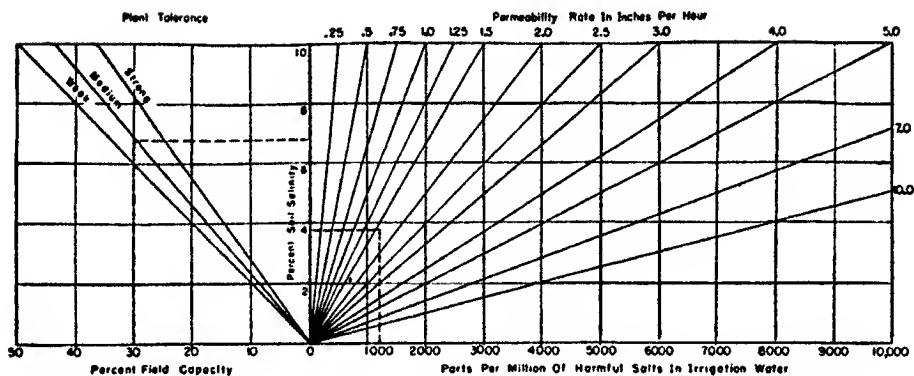


FIG. 1. QUALITY OF IRRIGATION WATER AS RELATED TO SOIL SALINITY AND PLANT TOLERANCE

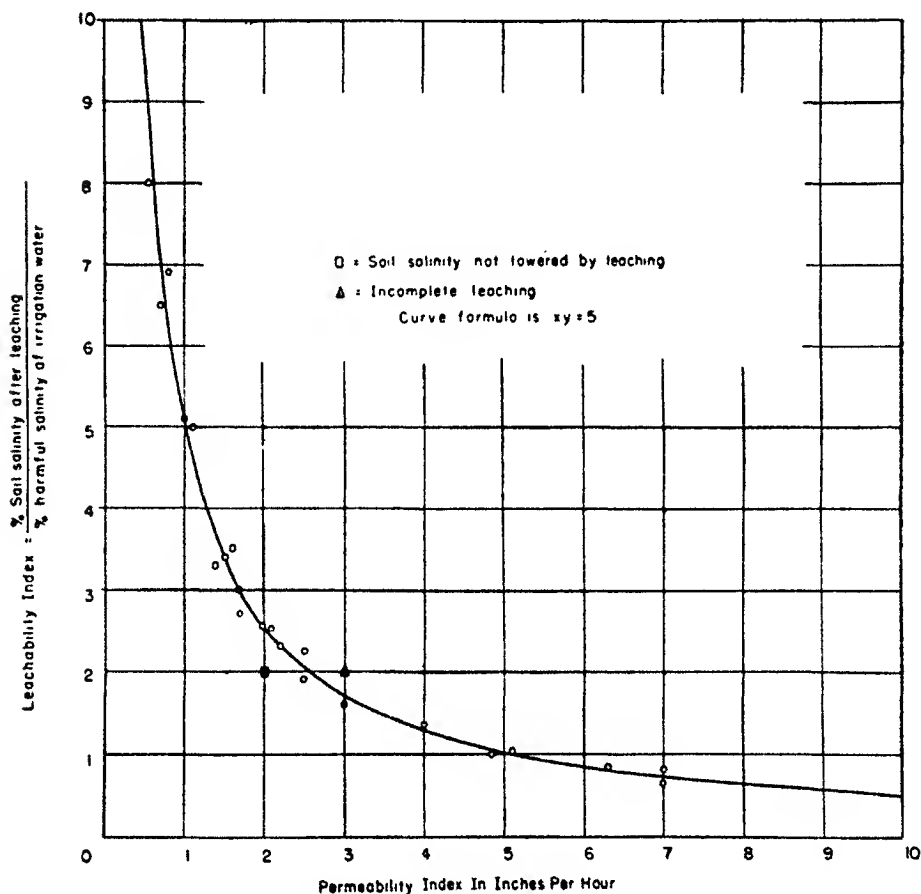


FIG. 2. CORRELATION BETWEEN LEACHABILITY INDEX AND PERMEABILITY INDEX AS REFLECTED BY FIELD TESTS

As a basis for comparison, if the percentage of soil salinity is:

1. In excess of the limit of tolerance, it is unsuitable for crop production.
2. More than 75 per cent of the limit of tolerance, crop production is doubtful.
3. Between 50 per cent and 75 per cent, it should produce fair crops.
4. 25 per cent to 50 per cent, good crop production.
5. Less than 25 per cent, excellent crop production.

The next step is to determine whether the present salt content of the soil is likely to increase or can be reduced. This is predetermined by the salt content of the irrigation water and the rate it can be run *through* the soil. If a perfect leaching could be accomplished, the soil solution could be reduced to the same concentration as the irrigation water. This perfect leaching, however, is far from obtainable under field conditions. There appears to be a definite correlation between the soil permeability and the nearness to which the perfect leaching can be approached. By use of lysimeters and field observations, a ratio can be established between the percentage of harmful salinity of the irrigation water and the percentage of salinity of the soil after leaching. This might be called the "leachability index." On the basis of information available, the correlation between the permeability index ( $P$ ) in inches of water per hour and the leachability index ( $L$ ) is as follows:

$$P \times L = 5 \text{ (fig. 2)}$$

Thus, if field capacity and permeability index of the soil and quality of the irrigation water are determined, the salinity level at which we may expect to operate with an efficient irrigation and drainage system can be calculated, as follows: *Expected soil salinity level equals percentage harmful salts in irrigation water times 5, divided by permeability index in inches per hour.*

For example, using water with 1160 p.p.m. harmful salinity on a soil with a permeability index of 1.5 inches per hour:  $(0.116 \times 5) \div 1.5 = 39$  per cent is the expected soil salinity level. (For graphic solution see right hand side of figure 1.)

Thus, with a limit of tolerance of 69 per cent and an expected salinity level of 39 per cent, the index of use is  $\frac{39}{69} = 56$  per cent, or fair.

#### DISCUSSION

The analysis also points out some of the conditions that must be controlled or corrected to establish irrigation and drainage systems.

The measured data on which this information is based are limited, but the correlation is so striking it cannot be ignored (fig. 2). Although the true correlation may not be this simple, the use of the formula  $P \times L = 5$ , has been shown to be practical in field applications using fairly broad ranges in field capacity and permeability for identifiable soil units.

Leaching was accomplished on field basis in level basins. Permeability indexes were obtained by field tests using concentric rings and a 2-inch constant head of water. Cumulative rates were plotted, and the point at which the curve leveled to a nearly constant increment rate was used as the permeability index. In selec-

tion of sites, the salinity of the water and soil was checked by use of an electric bridge measuring resistance. Enough soil samples were analyzed for salt content to indicate that the results obtained by the bridge were suitable for this study and field use. All water samples were analyzed in the laboratory to determine harmful salts. None of the tests were run on areas giving indications of black alkali, but it is probable that the same results can be obtained, as one of the most detrimental effects of black alkali is the reduction of permeability.

#### SUMMARY

Only salts of high solubility seriously affect osmotic tension.

Excess sodium ions give rise to a (black) alkali condition in soils.

Presence of toxic elements must be considered in ascertaining the quality of water for use in irrigation.

The field capacity and permeability of the soil are controlling factors in determining the potential use of saline irrigation water.

Percentage of field capacity times percentage of concentration plant will tolerate equals percentage of soil salinity plant will tolerate.

Expected soil salinity level equals percentage harmful salts in irrigation water times 5, divided by permeability index in inches per hour.

Expected soil salinity level in per cent divided by the percentage soil salinity the plant to be grown will tolerate equals the index of use in per cent.



# THERMODYNAMICS OF SOIL MOISTURE

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Various problems of soil physics involve the combined influence of capillarity, gravity, and the concentration of the soil solution. In regions of soil well above the ground-water level there are extensive air-water and particle-water interfaces. As has been suggested by Elefsen and Anderson (1) and others, various thermodynamic functions are important in describing the state of the soil moisture.

Partly dry soil is a complex system, including air and water vapor, water, and the solid soil particles, each phase being separated from the neighboring one by a surface of discontinuity. If we confine our attention to the liquid phase or to the vapor phase in its equilibrium state, this state may be defined completely by three coordinates. For example, we may select the temperature, the pressure, and the elevation, all other coordinates being determined by these three. It should be noted that because of the adhesion field in the neighborhood of the soil particle, there would, in general, exist pressure gradients in random directions. If, however, the problem be construed macroscopically, the hydrostatic pressure immediately beneath the curved interface in the "deep" water region would suffice as one of the three thermodynamic coordinates. This would depend, of course, upon the pressure in the air phase as well as upon the elevation.

## THE SECOND LAW OF THERMODYNAMICS

The second law of thermodynamics may be stated thus, "for all spontaneous reactions or natural processes the entropy of the universe must increase." It follows, then, that a system is at equilibrium if its entropy is at a maximum. Because of its broad generality, the second law is not immediately adapted to the solution of particular problems, but it can be shown on the basis of the second law that the Gibbs zeta function tends to decrease for thermodynamic processes that take place at constant temperature and pressure in simple systems involving but two independent variables. On the same basis, it can be shown for such a system that the Gibbs psi function decreases at constant temperature and volume, and that the Gibbs chi function decreases at constant pressure and entropy.

For these simple systems the combined first and second laws may be written for a reversible process,

$$TdS = dU + PdV, \quad (1)$$

<sup>1</sup> Graduate student. The author wishes to recognize the valuable assistance rendered by Willard Gardner, head of the department of physics, in the preparation of this paper.

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$T$  representing the absolute temperature,  $S$  the entropy,  $U$  the internal energy,  $P$  the pressure, and  $V$  the volume. The zeta function takes the form

$$\zeta = U + PV - TS, \quad (2)$$

and these equations lead immediately to

$$d\zeta = VdP - SdT, \quad (3)$$

and the vanishing of  $dP$  and  $dT$  constitutes a necessary and sufficient condition for equilibrium.

In the case of soil moisture equilibrium, the elevation being regarded as constant, equations (1), (2), and (3) would apply, but if the pressure is a function of the elevation,  $z$ , as expressed by either of the equations,

$$P = P_0 - \rho gz \quad (4)$$

$$P = P_0 e^{-\alpha z}, \quad (5)$$

equation (3) would take the corresponding forms,

$$d\zeta = V(dP_0 - \rho g dz) - SdT \quad (6)$$

$$d\zeta = V(e^{-\alpha z} dP_0 - \alpha P dz) - SdT. \quad (7)$$

In both cases the right-hand members would vanish when, and only when,  $dP_0 = dz = dT = 0$ . The zeta function of equation (2) would not be uniform throughout either phase.

If, however, we add to the right-hand side of equation (1) the gravitational work term  $gdz$ , combine with the zeta function the gravitational potential function  $gz$ , and interpret the volume in equations (6) and (7) as the volume per unit mass,  $v$ , we may write

$$\phi = \zeta + gz, \quad (8)$$

to replace equation (2), and equation (6) would thus take the form,

$$d\phi = vdP_0 + zdg - sdT, \quad (9)$$

and, inasmuch as  $g$  is constant, the differential of the potential  $\phi$  will vanish when  $dP_0 = dT = 0$  whether or not  $z$  is constant.

#### THE FREE ENERGY CONCEPT

In the following quotation by Lewis and Randall (5, p. 158), the symbol  $F$  is used for the zeta defined in equation (2):

"Thus, in any process occurring at constant temperature and pressure  $F_a - F_b$  represents the maximum of work which can be obtained from a given process and applied to useful purposes. It is for this reason that  $F$  is known as the *free energy*."

Reference is made frequently in recent literature in the field of soil physics to what is called the *energy method of studying the moisture of the soil*. Such expressions as *pressure energy* appear with the implication at least that the  $PV$  term of



equation (2) and likewise the  $PV$  term of the Bernoulli equation may be regarded as representing energy.

Epstein (2, pp. 87, 88, 89) suggests that the name *free energy* is not well chosen for this zeta function. All the terms on the right of equation (2) have the dimensions of energy, and the first term  $U$  does, of course, represent energy, but it would be difficult to interpret the other terms as representing energy in the general case.

Gardner and Chatelain (3) have pointed out certain applications of the zeta function that seem to be contradictory, and it seems likely that these difficulties may have been caused, in part at least, by misinterpretation of the physical significance of this function.

#### THE POINT OF VIEW OF STATISTICS

Haas (4, pp. 276, 277) applies the general statistical equation,

$$\ln W = \frac{B - \psi}{\theta} \quad (10)$$

to the distribution of energy, the term  $B$  being replaced by the energy  $U$ , and shows that for a general thermodynamic system involving any number of independent parameters, the element of work  $dA$  may be expressed thus,

$$dA = -dF + (\partial F / \partial \theta) d\theta, \quad (11)$$

for a reversible process,  $F$  being used for his symbol  $\psi$ ,  $\theta$  representing the modulus of distribution for heat energy. He points out (4, pp. 302, 303) that  $\theta$  is directly proportional to the absolute temperature  $T$ . If, therefore, we replace  $\theta$  by  $kT$  and define the term  $k \ln W$  as the entropy,  $S$ , we are able to show that the function  $\psi$  corresponds to the Helmholtz free energy function, for which the symbol  $F$  has been substituted above. It is equal to  $U - TS$  of equation (2).

He also points out (4, p. 312) that if a more general thermodynamic potential function  $\phi$  be defined thus,

$$\phi = U_1 u_1 + U_2 u_2 + \dots + U_i u_i + U - TS, \quad (12)$$

in which the  $U_i$  are generalized forces and the  $u_i$  are generalized displacements, and the differential of this is combined with equation (11), we obtain,

$$d\phi = -SdT + u_1 dU_1 + u_2 dU_2 + \dots \quad (13)$$

In the notation of Haas, the  $u_i$  represent what are known as extensive variables, corresponding to such quantities as volume and entropy, and the  $U_i$  represent intensive variables, such as pressure and temperature.

It is important to observe that the differentials on the right-hand side of equation (13) are the differentials of the intensive variables, as is true of equation (9); also that equation (11) represents a combination of the first and second laws for the general case, as does equation (1) for the other. It may be shown also for this general case that replacing any one of the terms  $u_i dU_i$  on the right-hand side of equation (13) by the term  $U_i du_i$  and equating the result to zero would not

necessarily represent the condition for equilibrium of this more complicated thermodynamic system.

For example, in reference to the raindrop problem considered by Lewis and Randall (5, pp. 247-252) let us express the thermodynamic potential function in the form,

$$\phi = U + PV + \gamma\sigma - TS, \quad (14)$$

assuming that the interface of the raindrop represents the surroundings and not a part of the thermodynamic system. The combined first and second laws would then be written,

$$TdS = dU + PdV + \gamma d\sigma, \quad (15)$$

$\gamma$  representing the surface tension of the interface and  $\sigma$  its area. The surface tension depends upon the chemical character of the drop as well as upon the temperature. The quantities  $U$ ,  $V$ , and  $\sigma$  are here regarded as functions of the mass and the thermodynamic coordinates. If we compute the differential of equation (14) and then eliminate the  $TdS$  term by means of equation (15), we obtain,

$$d\phi = -SdT + VdP + \sigma d\gamma. \quad (16)$$

The variables the differentials of which appear in this equation are all intensive, and it is the vanishing of these differentials that determines a state of equilibrium.

On the other hand, had the term  $\gamma\sigma$  been omitted from equation (14) equation (16) would have taken the form,

$$d\phi = -SdT + VdP + \gamma d\sigma. \quad (17)$$

The right-hand members of equations (16) and (17) differ only in the last term, and it is apparent that they cannot vanish together unless  $\sigma$  is a linear function of  $\gamma$ .

Equations (8) and (9), applying to soil moisture in the gravitational field, are also special cases of equations (12) and (13).

#### SUMMARY

The fundamental purpose of this article is to emphasize the importance of exercising care in applying the laws of thermodynamics to problems having to do with soil. Equation (11) is rewritten in the familiar form, use being made, however, of generalized coordinates,

$$TdS = dU + U_1 du_1 + U_2 du_2 + \dots + U_i du_i$$

The fact is emphasized that this is a combination of the first and second laws in generalized form, and that, when combined with equation (12), which constitutes the definition of the generalized thermodynamic potential or zeta function, it leads immediately to equation (13), the vanishing of the right-hand member of which for a reversible process constitutes a necessary and sufficient condition for thermodynamic equilibrium.

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# DURABLE ASBESTOS TENSION TABLES<sup>1</sup>

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The soil moisture tension table of Leamer and Shaw<sup>3</sup> has made possible the rapid routine determination of soil macroporosity on field-fresh samples. Previous to development of this apparatus, the tension funnel, pressure plate, and other methods used to determine soil moisture tension relationships were slow and adapted to the simultaneous analysis of a very limited number of samples. Large numbers of samples could not be taken at one time for comparison without the use of questionable storage methods. Other methods are still needed to study soil moisture at higher tensions, but since it is often desirable to make low tension determinations quickly and to compare the volume of larger voids in many samples at the same time, the tension table has come to be widely used.

As reported, the first tension table was constructed with a rectangular metal base partly covered with a screen and with a wet blotter rolled down evenly over the screen, so as to overlap and seal to the base all around the edge. A water outlet was provided by means of a tube soldered in a hole through the base with a suitable length of rubber hose connected to a water-leveling jar which, in turn, could be raised or lowered to vary the moisture tension in the blotter. To establish continuous water tension between the level jar and the blotter, the screen had to be flooded, the tube filled with water, and the blotter rolled down firmly to prevent air entrapment under the blotter or in the tube. The common type of tension table now in use has a glass-plate base, through which the operator can readily see the screen and detect any entrapment or entry of air through or under the blotter.

Although a boon to soil scientists, the tension tables now in use have a number of weaknesses which some workers have tried to overcome by modification of the original design. The blotters, when wet, are easily torn and may be punctured by frayed edges of the wire screen. If allowed to dry out, blotters wrinkle and have to be replaced. Because of their low air-entry value, usually less than 100 cm. water tension, their use is limited to the study of the low-tension moisture range. With continuous use of the blotters, their pores become clogged with clay and replacement is necessary. After every period of disuse, when a fresh supply of samples is brought to the laboratory for analysis, the table must be readied for use and a new blotter wetted and rolled into place. Since the blotters

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<sup>2</sup> Soil physicist, Division of Soil Management and Irrigation, and senior agricultural engineer, Division of Farm Machinery, respectively.

<sup>3</sup> Leamer, R. W., and Shaw, B. A simple apparatus for measuring noncapillary porosity on an extensive scale. *Jour. Amer. Soc. Agron.* 33:1003-1008. 1941.

are cheap, the necessity for frequent changes is not of economic importance except for the time used for this operation. It would be more convenient if a table could be constructed with a stable membrane such that the surface could be washed free of soil whenever necessary and could be quickly available for use whenever needed. Another rather serious difficulty often experienced with the blotter type tension table arises from the necessity of flooding the screen to exclude air. The table is usually assembled on a laboratory bench near a sink, accessible to a steady supply of water and to the drain. In the flooding operation, unless special precautions are taken, water is spilled over the bench and on the floor.

The suggestion of Olmstead<sup>4</sup> that possibly a porous plate would be more suitable than the blotters for his purpose stimulated the authors to investigate other conducting materials such as plaster of paris and asbestos. Earlier moisture tension studies of various porous materials indicated that water-stable asbestos board offered the most promise. Calibration of one particular sample showed it to be a good moisture conductor and to have an air-entry value of more than 200 cm. water tension. In the use of asbestos board as the tension membrane and the other modifications described hereafter, the authors feel they have developed moisture tension apparatus which is not only rapid but durable, compact, and available for use at all times. Also, the necessity of a separate soaking tray is eliminated. The soils can be placed on the membrane and soaked prior to application of tension.

#### CONSTRUCTION

The tension table trays are constructed of brass to inhibit corrosion. The asbestos board should be water stable and have an air-entry value a little higher than the maximum tension it will ever be desirable to use. At the same time, the material should conduct water rapidly enough that the soil samples rather than the membrane will largely determine the time needed for tension equilibration. The board should be thick enough to be durable when wet but thin enough to bend slightly to conform to slight curvatures in the tray without cracking. The material used by the authors was obtained in rectangular pieces 42 by 48 inches with a thickness of  $\frac{1}{8}$  inch.<sup>5</sup> Tests of one sample indicated air entry at about 250 cm. water tension and ability to conduct water at the rate of  $6 \times 10^{-6}$  ml. per square centimeter board surface per centimeter water tension per second. This means that under a tension head of 60 cm. water, more than 2 ml. water can pass through 100 sq. cm. board surface in 1 minute. The size of one of the tension table units was determined largely by the width of sheet brass available and the size of the asbestos board. The sheet brass used was 16 inches wide, and six pieces 16 by 21 inches can be cut from a large asbestos board 42 by 48 inches without waste. A unit constructed from a board cut this size can be readily immersed in any ordinary laboratory sink for soaking and air removal.

<sup>4</sup> Olmstead, L. B. Personal communication, 1947.

<sup>5</sup> Obtained from Central Scientific Co., Chicago, Ill., Cat. No. 10140 C.

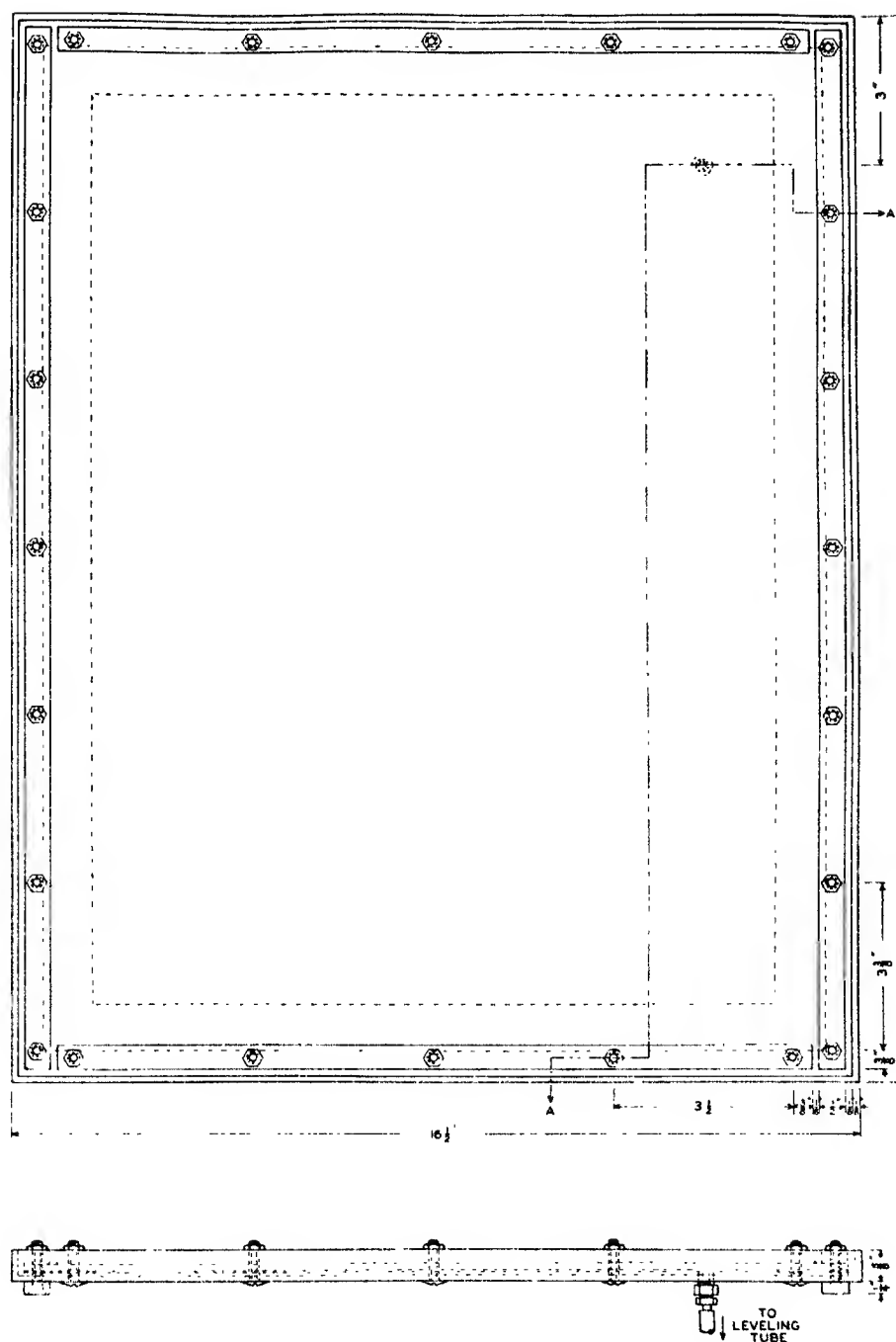


FIG. 1. DESIGN OF A TENSION TABLE UNIT

The diagram for the construction of one unit is shown in figures 1 and 2. Pieces of  $\frac{5}{8}$ - by  $\frac{5}{8}$ - by  $\frac{1}{8}$ -inch brass angle were cut, notched, fitted together, and brass-welded to form a tray into which a 16- by 21- by  $\frac{1}{16}$ -inch brass sheet will fit loosely. The sheet was soldered in place by playing a small torch flame along the outside of the angle wall while solder wire was allowed to melt and run into place in the acid-treated crack between angle and sheet. Less solder is required and a smoother seal can be made this way than by using a heavy tapered copper-soldering tool. Although the tray tends to warp slightly with the necessary heating, it can be readily straightened after cooling. The hole for the water connection was placed near one corner to facilitate air removal when readying the table for use. The corner selected should be determined largely by the loca-

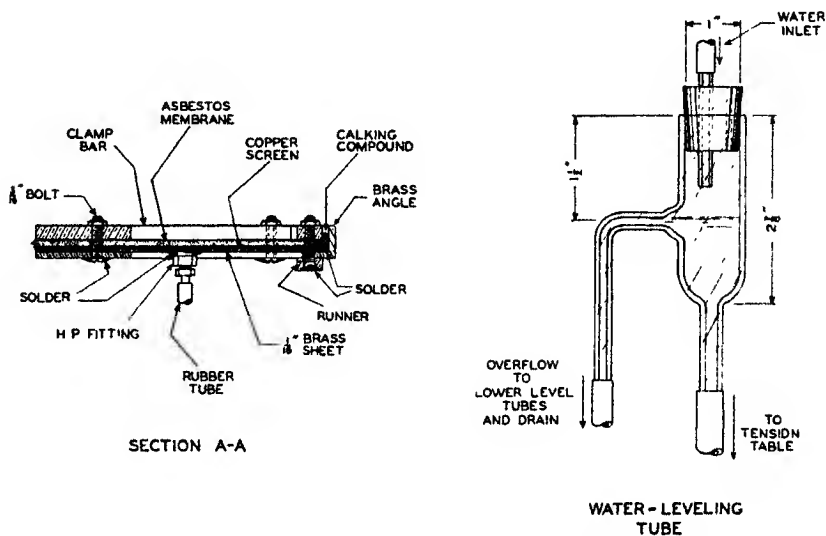


FIG. 2. SECTION A-A OF FIGURE 1 AND DESIGN OF A WATER-LEVELING TUBE

tion of water source and drain with respect to the placement of the apparatus in the laboratory. It was found convenient to drill the hole about 4 inches diagonally inside the corner and tap it for a  $\frac{1}{8}$ -inch pipe fitting. A high-pressure fitting for  $\frac{1}{16}$ -inch copper tubing was screwed into place, sealed with solder under the tray, and ground down smooth on the upper surface. Seven holes lengthwise and five widthwise were drilled at equidistant spacings all around the tray  $\frac{1}{4}$ -inch from the inside edge. Runners on which the table rests or slides were cut from  $\frac{1}{2}$ - by  $\frac{1}{4}$ -inch brass bars to fit lengthwise under each side of the tray. Clamp bars were cut from the same stock to fit around the inside edge of the tray. The asbestos board was placed in the tray, the runners and clamp bars were clamped in place, and holes were drilled at the proper spacings. The holes in the tray were tapped for  $\frac{3}{16}$ -inch brass screws, and those in the clamp bars were reamed out with a  $\frac{3}{16}$ -inch drill. The runners were similarly reamed as well as countersunk so that the heads of screws inserted through the holes would be embedded flush



with the lower bar surface. A copper or brass screen was then cut to fit inside the tray so as to leave about an inch margin all around inside the holes, the asbestos board was placed in the tray, and the runners were fastened by  $\frac{3}{16}$ -inch brass bolts inserted through the countersunk holes and turned through the



FIG. 3. TENSION TABLE CABINET ASSEMBLED AND READIED FOR  
USE IN THE LABORATORY

threaded holes in the tray. The lengthwise clamps were then set in place with the bolt ends inserted through the holes in the bars and gripped down tightly on the asbestos boards with brass nuts on the bolts. Brass bolts were also turned up through the holes in the ends of the tray, and the end clamps likewise were gripped down on the asbestos board. If each of the bolt heads is sealed with solder, it will be more convenient to disassemble and reassemble the unit whenever

it becomes necessary to replace the membrane. Occasionally a tension table will leak air under high water tension. After the asbestos board is in place, filling the crack between board and tray wall with calking compound, placing a little around each bolt, will ensure against air entry under the membrane. Likewise, any crack or flaw observed in the membrane can be satisfactorily sealed with a little plaster of paris or Portland cement paste after the membrane is wetted.

After a tension table is assembled, air is removed by inverting and immersing in a sink partly filled with water. The outlet is connected to an aspirator by means of a length of rubber tubing having a short glass tube insert, and suction is applied until the water flowing through the glass tube is free from air bubbles. The unit is then lifted from the sink and placed in its position in the cabinet (fig. 3). The hose connection next to the aspirator is clamped before the connection is broken, and water is poured on the membrane to prevent air entry until connection to a water source can be made.

Each of the table units can be placed on a bench or table and connected to a water-level bottle or to a water-leveling device. In the cabinet assembly the table units are arranged one above another in a frame constructed of angle iron. Each unit is free to slide forward from its position like a drawer; then, after loading, unloading, or checking of the weights of samples on the table, it can be pushed back into place. Water for the cabinet is drawn directly from the city water line, a needle valve being used for adjusting the flow. If the water contains sediment or rust likely to clog the valve or strain the glassware, a filter or settling tank should be inserted ahead of the valve in the line. The cabinet should be placed near a floor drain or where it can be tapped into a low drain pipe. Each table hose is connected to the drawn-out stem of a small filter funnel. A small stream of water is introduced in the upper funnel through a glass tube in one hole in a two-hole rubber stopper. The extra hole functions to keep the water surface in the funnel at atmospheric pressure. The water overflows from the side arm of the top funnel and into the second funnel through the two-hole stopper and so on until the excess flows from the lowest funnel into the drain. The funnels are clamped to a section of pipe so that the water levels are the same distances apart as the corresponding table units. The pipe slides on a vertical journal clamped to arms welded to the cabinet. Set screws in the pipe are used to clamp it at any desired level from 0 to 80 cm. below each corresponding table unit. A collar can be clamped on the journal at a chosen tension level for convenience where one is interested in bringing soil samples to a fixed tension after saturation.

#### OPERATION

The sample cores of soil may be saturated by soaking them in a separate tray, following the method of Leamer and Shaw, before equilibration on the table. It is more convenient, however, to use the tension table itself for soaking samples. Where the sampling method of Lutz<sup>6</sup> is used, the soil boxes containing the cores

<sup>6</sup> Lutz, J. F. Apparatus for collecting undisturbed soil samples. *Soil Sci.* 64: 399-401. 1947.

are covered with a small piece of cheesecloth held in place with an elastic band. They are then inverted and placed on the tension tables, each table being loaded in turn by drawing it out from its rest position in the cabinet. The tables are then flooded by pouring water on the upper board surfaces, and the water-leveling device is raised and clamped in such a position that the water on the boards and that in each of the funnels are at corresponding levels. The raising of the leveling device from a lower level must be done in short stages over a period of 4 or 5 minutes. A rapid decrease in tension on the rubber tubes will cause water to

TABLE 1

*Time required for different soils to approach equilibrium at tensions of 20, 60, and 120 cm. water on tension table with asbestos board as membrane*

TIME	MOISTURE CONTENT											
	Norfolk sand			Davidson loam			Cecil clay			Houston clay		
hours	per cent*	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
Satura- tion...	25.5	26.8	25.8	27.5	33.1	29.2	41.6	40.3	40.4	90.8	91.2	83.6
Tension—20 cm. water												
2.....	17.3	18.8	18.3	18.4	21.3	18.1	29.5	29.6	29.6	45.3	45.8	44.2
5.....	16.9	18.4	17.8	18.1	20.7	17.8	29.4	29.4	29.4	44.9	45.5	43.9
8.5.....	16.6	18.1	17.3	17.8	20.3	17.6	29.3	29.3	29.1	44.5	45.0	43.8
12.....	16.5	17.6	17.0	17.5	19.8	17.6	29.2	29.1	29.1	44.4	44.8	43.3
Tension—60 cm. water												
4.5.....	6.9	7.7	7.3	12.5	13.0	12.7	27.2	26.5	26.4	38.9	39.4	39.1
8.....	6.4	7.3	6.8	12.2	12.7	12.4	27.0	26.4	26.2	38.6	39.3	38.8
12.....	6.3	7.0	6.8	12.2	12.5	12.5	26.7	26.3	26.3	38.6	39.0	38.7
Tension—120 cm. water												
6.....	5.0	5.6	5.0	10.4	10.2	10.5	25.3	24.7	24.9	36.7	36.7	37.0
22.....	4.7	5.2	4.9	10.3	10.1	10.5	25.2	24.6	24.8	36.1	36.4	36.7
27.....	4.7	5.1	4.8	10.3	10.1	10.3	25.2	24.6	24.6	36.1	36.4	36.6

\* Percentages by weight.

retreat from the funnels unless time is allowed for adjustment through the flow from the water source. After soaking for about 15 hours, the samples can be removed one at a time from the cabinet and weighed on a rapid and suitably accurate balance or scale. The samples are then replaced on the tables and the leveling device is dropped to the collar stop, which is set to give the desired tension. They are left under tension for 24 hours before being reweighed. If the true specific gravities and the total volumes of the soils under consideration are known, it is possible to calculate the solid soil volume and total porosity from the weight at some equilibrated tension, such as 60 cm., and the oven-dry weight of the soil. It was found that in several Alabama soils tested, covering a

range of textures from light sands to very heavy clay, the true specific gravity values varied no more than  $\pm 0.05$  from the value of 2.67. It is felt that the use of this value for an Alabama soil in the calculation of solid volume is more accurate than the use of an air pycnometer in making a direct determination. Thus, the data for macroporosity, total porosity, and volume weight can be obtained by soaking, equilibrating at the chosen tension (usually 60 cm.), weighing after removal of the cheesecloth, oven-drying at 105°C., and then weighing again. If one is interested in the significance of the so-called "unsaturated value," the weight after soaking can be obtained and the unfilled pore space after soaking can be calculated.

#### TEST OF THE APPARATUS

The results of a preliminary test of the asbestos board tension table are shown in table 1. Three samples each of four different soils were used, covering a range in texture from sand to heavy plastic clay (the Houston soil). The samples were taken with the Lutz<sup>6</sup> sampling device. For this size sample (height 3.5 cm. and volume 83 ml.), it is quite clear that 24 hours is more than adequate equilibration time for most soils at any tension to be used up to 120 cm. water. Admittedly, with very plastic clays, slow removal of water may continue to occur after 1 day, but such a change will be due largely to shrinkage rather than to removal from macropores.

#### SUMMARY

A modification of the soil moisture tension table of Leamer and Shaw is described. Water-stable asbestos board is used as a membrane, which is clamped over a copper screen in a tray constructed from angle and sheet brass. A method of arranging table units in a convenient cabinet form to conserve space is also described. The operation of the device is explained, and results are given for a test with soils including samples of a sand, a loam, and two clays. The results show that 1-day equilibration time is more than adequate for most soils to take them from saturation to any tension up to 120 cm. water.

# NYLON ELECTRICAL RESISTANCE UNIT FOR CONTINUOUS MEASUREMENT OF SOIL MOISTURE IN THE FIELD<sup>1</sup>

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This paper reports the development and refinement of a nylon absorption electrical resistance unit for making continuous measurement of soil moisture under field conditions. This nylon unit is capable of measuring soil moisture from saturation to almost air-dryness. It has proved far superior in performance to the fiberglass unit previously described (5). An advantageous feature of the nylon unit is its great sensitivity to changes of moisture at high levels of water content; in fact, the unit is more responsive and more sensitive to nearly saturated conditions than others thus far developed. Because of this characteristic, the nylon unit should be ideal for highway engineers and hydrologists who are especially interested in measuring the higher levels of soil moisture content. It should also be of service to agronomists and plant physiologists because it is capable of measuring a greater range of soil moisture than is the plaster of paris block (2, 4).

## PRINCIPLE OF NYLON UNIT

The nylon unit is made on the same principle as the plaster of paris block, wherein the electrodes are imbedded in the block in a constant environment, which minimizes the effects of external soil factors such as degree of compaction, texture, structure, salt content, and electrical lines of force. Only units with such internal electrodes are successful in measuring soil moisture under field conditions. Units with external electrodes have proved completely unsuccessful in this respect (5).

The nylon unit, as finally perfected and embodying the principle of the plaster of paris block, is shown in figure 1. It consists of two perforated, extremely thin nickel plates, or two pieces of fine monel screen, acting as electrodes, to which are silver-soldered wire leads. These electrodes are separated by wrappings of nylon. The whole assemblage is then placed in a perforated nickel case and subjected to high pressure, the edges of the metal thus being mechanically united to hold the enclosed assemblage permanently. The enveloping case has  $\frac{2}{16}$ -inch square holes,  $\frac{1}{4}$ -inch center straight, and is 64 per cent open. The holes cover the entire surface of the case, thus affording the absorbent extensive exposure to the soil.

Like the plaster of paris block, the nylon unit absorbs moisture from the soil and gives it up to the soil very readily. When the nylon unit is buried in the soil, its moisture content tends to be in equilibrium with that of the soil. The

<sup>1</sup> Contribution from the Soil Science Section of the Michigan Agricultural Experiment Station, authorized for publication by the director as Journal Article No. 1009.

electrical resistance of the unit varies with its moisture content and, by calibration, becomes an index of moisture in the soil.

Also, like the plaster of paris blocks, the nylon units provide a continuous measure of field moisture variations. The units may be imbedded in the soil at the desired depth and left there permanently. Soil moisture is determined by measuring the electrical resistance of the unit. Resistances are then translated into moisture percentages by means of previously determined calibration curves.

Although their construction is somewhat complicated and delicate, nylon units, when uniformly made,<sup>2</sup> give surprisingly similar reading at similar moisture levels. Newly constructed units immersed in tap water show a variation from about 0 to 15 ohms in initial resistance.

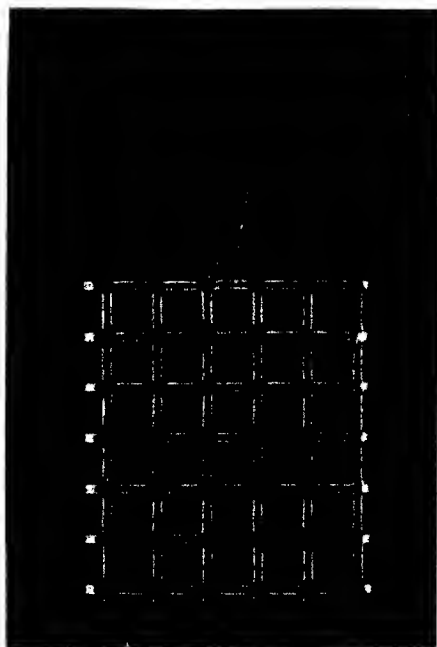


FIG. 1. NYLON ELECTRICAL RESISTANCE UNIT WITH INTERNAL ELECTRODES

An interesting feature of these nylon units is their outer metal case, which acts as a shield and which almost entirely eliminates electrical lines of force.

The nylon unit has virtually no lag in its response to changes of soil moisture. Two factors are responsible for this: the extreme thinness of the unit; and the extremely low water-holding power of the nylon fabric.

#### RESISTANCE-MEASURING INSTRUMENTS

The special Wheatstone bridge used for the plaster of paris block method (4) of determining soil moisture percentages is also applicable to the nylon units.

<sup>2</sup> Standard nylon units are manufactured by the Wood and Metal Products Company, Bloomfield Hills, Michigan.

As finally perfected, it has proved entirely satisfactory. It is portable and of rugged construction. It ranges from 0 to 5,000,000 ohms, is accurate, has a powerful signal, has a definite null point, and performs satisfactorily even under adverse conditions such as low temperature, wind, and noise.

#### CALIBRATION

For research investigations it is considered advisable to calibrate the nylon absorption units for each soil installation.

A satisfactory calibration procedure consists of placing 20 gm. of sieved air-dry soil in the bottom of a small painted metal pan, 1 by 2 by 2 inches. On top of this leveled soil is placed the unit. To ensure its remaining in place and leaving undisturbed the sample in which it is embedded, very thin, flexible leads are firmly clipped to the rim of the pan (5, p. 224). Then another 20 gm. of soil is placed over the unit. The pan is tapped horizontally and vertically to pack and level its contents. Water is gently added until the soil is saturated and a small quantity of excess water covers the surface.

Because the pan bottom is not perforated it does not allow drainage nor does it permit replaced air to escape. Sometimes air bubbles are trapped in the electrode grids, and as a result, the unit floats upward. This difficulty is remedied by gently pushing the unit down with a thin sheet of metal 2 inches wide and gently tapping, which releases nearly all bubbles. In rewetting for subsequent drying cycles on the same sample, a similar procedure is followed. The unit is pushed down and lightly tapped after every addition of water. These precautions to ensure adequate and uniform contact between soil and absorbing surfaces are vital for successful calibration.

After wetting, the sample dries slowly under ordinary temperature and humidity conditions prevailing in the laboratory. At frequent intervals, depending on the drying rates, resistances are measured by means of the soil moisture bridge. For each resistance value, a corresponding moisture value is obtained by weighing the entire pan, unit, and soil. A Toledo balance with a sensitivity of 0.5 gm. has proved convenient for this purpose. Moisture percentages are calculated from the net losses and the already determined oven-dry sample weight. Although some samples shrink and crack when approaching air-dryness, these structural changes do not appear to influence the accuracy of the calibration method, except that certain soils having a very high percentage of shrinkage may pull away from the lower side of the unit, with the result that the bottom layer of soil may not be so dry as the readings would indicate. However, this is still the simplest and most rapidly accurate method of calibration yet devised.

Probably the greatest source of error in calibrating the nylon units in the laboratory is the tendency of air bubbles to adhere to the screen electrodes. The presence of air bubbles causes the electrical resistance to be higher. These air bubbles, however, tend to exit of their own accord. Under field conditions, however, the units undoubtedly will perform accurately and yield smoother curves than they do in the calibration pans, where only 40 gm. of soil is used. The obvious reason for this is that when the units are buried in the ground the

weight of the soil mass helps to maintain an intimate contact between soil and unit, and the air bubbles have a better chance of escaping.

#### PERFORMANCE CHARACTERISTICS

To obviate misunderstanding, certain terms must be defined. For example, "saturation point" means the critical point at which the excess water disappears

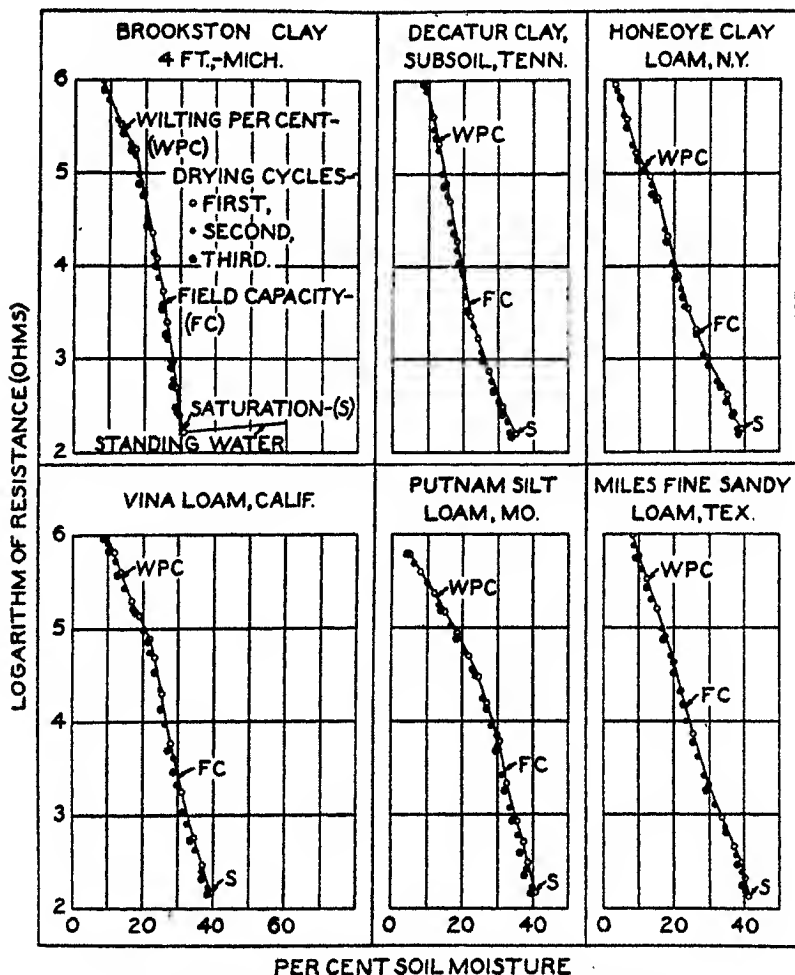


FIG. 2. SENSITIVITY, ACCURACY, AND REPRODUCIBILITY OF RESULTS WITH THE NYLON UNIT

in the soil and air begins to enter the soil pore space. It is at this critical point that the electrical resistance begins to rise.

As various investigators have found that, for practical purposes, moisture equivalent is approximately the same as field capacity (6), the two terms are synonymous here. This value was determined by the suction method (1).



The difference between "saturation point" and "field capacity" is regarded here as gravitational water.

With these explanations, a consideration of the moisture curves in figure 2 is in order. These curves illustrate the shape, degree of sensitivity, accuracy, reproducibility, and range of soil moisture content that the nylon units yield.

At the high moisture content the curves have generally a steep gradient, indicating high sensitivity to changes of moisture at the wet levels. This is a very useful feature of the nylon units, because it is at this high level of moisture content that a sensitive and accurate method is most needed, and it is here that all other electrical methods have failed.

The moisture curves also show that the unit gives satisfactory accuracy and reproducibility. As indicated, each soil was dried three times and each curve is made up of points obtained from three successive drying cycles. In view of the fact that only 40 gm. of soil was used in the calibration pan, that the soil tended to warp and crack upon drying, that there was no weight pressing on the soil layer for intimate contact between soil and unit, this degree of accuracy and reproducibility is surprisingly good.

The moisture curves further show that the measurement range of the nylon units extends from saturation to almost air-dryness. The amount of moisture or gravitational water between saturation and field capacity is considerable, more than 15 per cent in some of the soils. This signifies that the unit is able to function at or near the saturation point of the soil.

It is of interest to note that the field capacity falls within the range 1,800 to 3,000 ohms, and the wilting percentage between 150,000 and 400,000 ohms. The saturation point, on the other hand, fluctuates between 100 and 250 ohms.

In the curves, the moisture measurement is represented up to 1,000,000 ohms. Since the moisture bridge reads up to 5,000,000 ohms, the moisture measurement can be extended to this higher resistance value.

#### MOISTURE CURVES OF VARIOUS TYPES OF SOIL

Figures 3 to 6 present moisture curves for some of the 47 soils from many parts of the United States and from Canada, including surface soils, subsoils, muck, sand, colloidal clays, laterites, saline soils, and soils very low in soluble salts, used to test the nylon unit very thoroughly, to discover its limitations and weaknesses, and to establish the characteristic pattern of moisture curves that the unit yields.

Examination of the 47 moisture curves revealed four dominant patterns.

The first pattern is characterized by a very steep gradient as the moisture content of the soils increases. This pattern is exemplified by Miami silt loam subsoil (fig. 3) and by Brookston clay subsoil (fig. 2), both of which are very low in soluble salt content. The same pattern is also exemplified by sandy loams such as the San Joaquin and the Sierra (fig. 3), both of which are high in soluble salts.

The second pattern is characterized by a gentle slope at first and then by a steep gradient as the soil moisture content increases. This pattern is typically

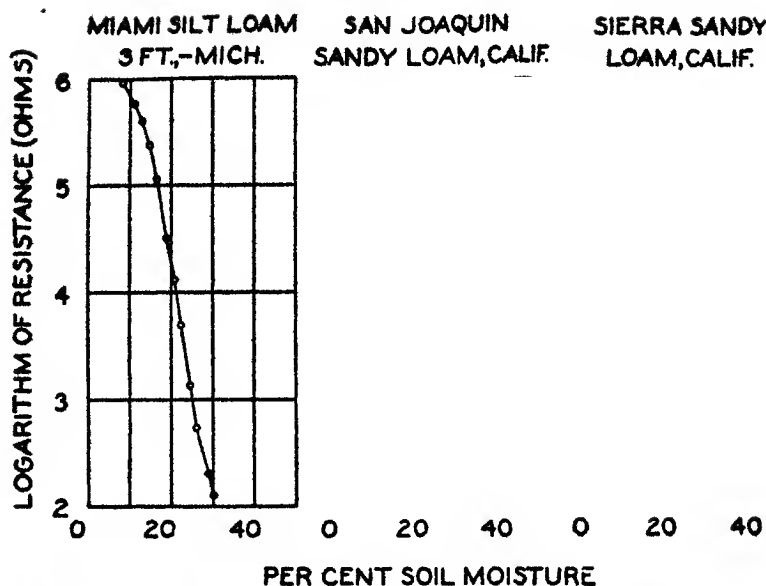


FIG. 3. MOISTURE CURVES OF SOILS, SHOWING THE FIRST DOMINANT PATTERN YIELDED BY THE NYLON UNIT

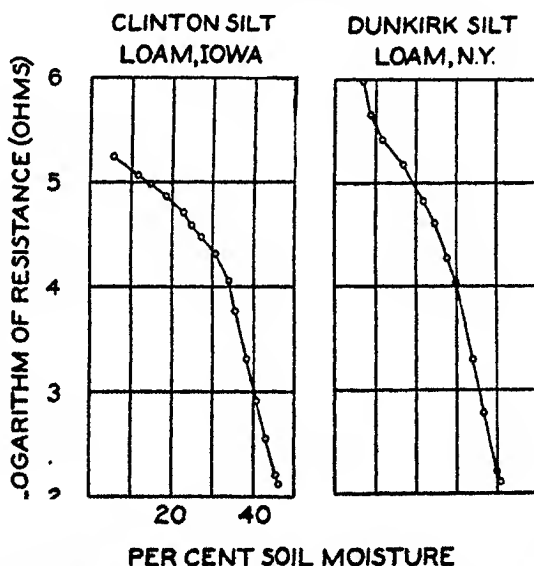


FIG. 4. MOISTURE CURVES OF SOILS, SHOWING THE SECOND DOMINANT PATTERN YIELDED BY THE NYLON UNIT

illustrated by Clinton and Dunkirk silt loams (fig. 4), both of which are of average fertility.

The third pattern consists of a steep gradient at first and then by a pronounced leveling off. This pattern is illustrated by Coachella fine sand and by Imperial clay (fig. 5), which contain 1.1 and 2.4 per cent soluble salts respectively.

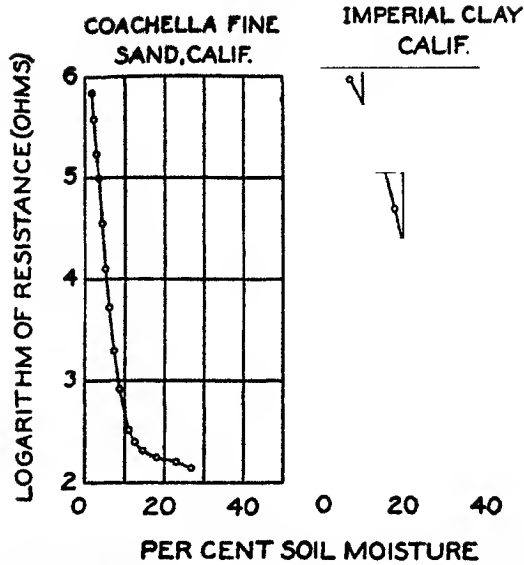


FIG. 5. MOISTURE CURVES OF SOILS, SHOWING THE THIRD DOMINANT PATTERN YIELDED BY THE NYLON UNIT

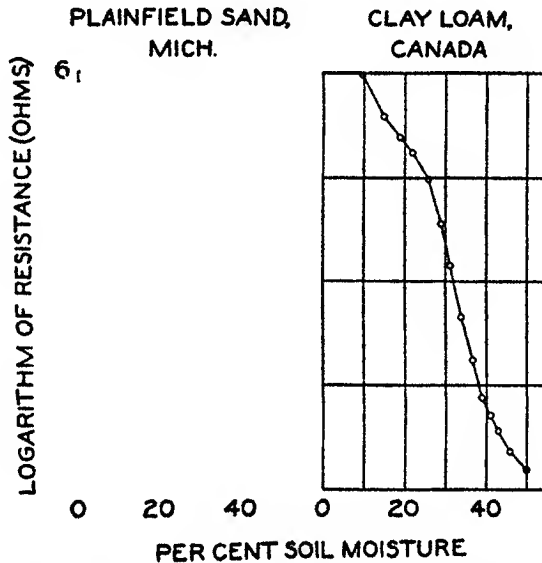


FIG. 6. MOISTURE CURVES OF PLAINFIELD SAND, SHOWING THE FOURTH DOMINANT PATTERN YIELDED BY THE NYLON UNIT; AND OF CANADIAN CLAY LOAM, COMPARATIVELY HIGH IN FERTILITY

The fourth dominant patterns in shown by Plainfield sand (fig. 6). The curve for this soil shows a very steep gradient and then an almost flat line for the major part of the moisture content. This type of pattern indicates that the nylon unit, like the plaster of paris block, is incapable of measuring moisture in pure sands because the absorption pull, or tension, of sand for water is very weak.

Thus, with the exception of sand, the nylon unit is capable of measuring moisture in all the different classes and types of soil varying greatly in salt and organic matter contents.

It will be noted that at the resistance level of 1,000,000 ohms, the moisture content of many soils approaches that of the air-dry condition. With other soils, especially the colloidal clays, the resistance may increase to almost 5,000,000 ohms before the moisture content approaches that of the air-dry condition.

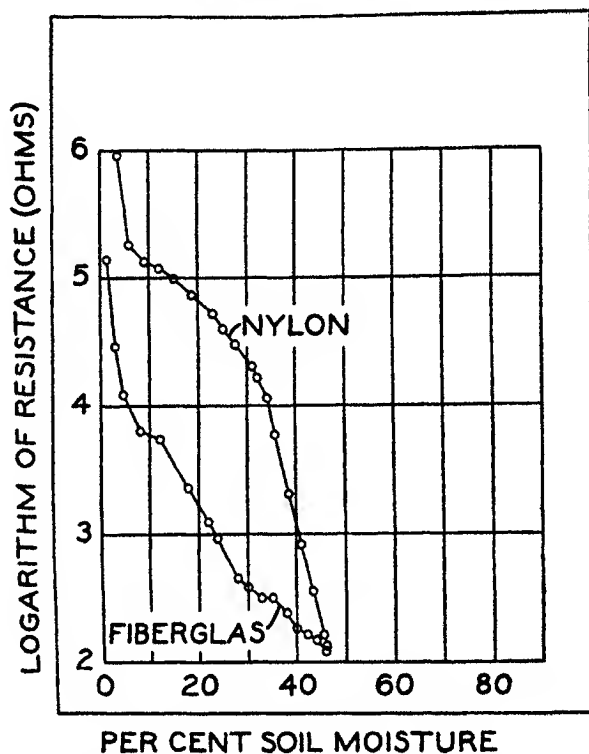


FIG. 7. COMPARISON BETWEEN MOISTURE CURVES OF CLINTON SILT LOAM OBTAINED BY NYLON AND FIBERGLAS UNITS

#### COMPARISON BETWEEN NYLON AND FIBERGLAS UNITS

As has already been mentioned, the nylon unit gives superior performance to the fiberglass unit. Figure 7 shows the moisture curves obtained by the two units in Clinton silt loam. Obviously, the nylon unit is more sensitive than the fiberglass unit. For example, a decrease of 23 per cent in moisture content causes the electrical resistance of the fiberglass unit to rise to only 1,000 ohms, whereas the same decrease in moisture content raises the electrical resistance of the nylon unit to more than 50,000 ohms. In addition, the nylon unit gives a more smoothly regular type of moisture curve than does the fiberglass unit.

Admittedly, fiberglass has more buffering action than nylon, but this buffering action is not sufficient to overcome or eliminate the influence of salts, and there-

fore, fiberglass has practically no advantage over nylon in this respect. For example, in soils such as clay loam (fig. 6), which is comparatively high in fertility, and Brookston clay subsoil (fig. 2), which is deficient in soluble salts, the fiberglass unit acts about the same as the nylon unit.

Tests extending over more than 4 years have shown that nylon is a very durable fabric and even when buried in the soil, has a long life-expectancy. In addition, nylon will not react chemically with soils and does not absorb and accumulate salts to any marked degree. Fiberglass, on the other hand, seems to react chemically with some soils and to absorb appreciable quantities of salts, with consequent change in the calibration of the unit.

#### EFFECT OF SALTS

As previously mentioned, nylon is an inert fabric and has virtually no buffering action. But this lack of buffering action does not seem to be a serious handicap, since each soil is calibrated and the calibration takes into account the physical and chemical characteristics and the salt content. The various moisture curves already presented show that the performance of the nylon unit is reasonably stable and consistent, especially for the second and third drying cycles, strongly indicating that the unit rapidly reaches equilibrium with the surrounding environment. The influence of salt concentration at different times within the same soil is considered unimportant in average conditions.

Besides the nonreaction, chemically, of nylon with soil and the nonabsorption and nonaccumulation of salts, several factors tend to minimize the effect of salt content on the nylon unit. Of these, the most important is the relatively large surface of the unit. The larger the surface, the smaller will be the effect of differences in salt content in different soil samples.

Undoubtedly, the dominant effect of high salt content in the soil is to make the nylon unit less sensitive to moisture changes and to limit its sensitive resistance range. Excellent illustrations of this are presented in such soils as Imperial clay and Coachella fine sand (fig. 5) which are both saline. In these two soils the nylon unit is not very sensitive to changes of moisture in the upper levels. This is in striking contrast to the Brookston clay and Miami silt loam subsoils, both of which are low in soluble salt content. In these soils the unit responds with high sensitivity to changes of moisture, as indicated by the steep gradient of the curves.

#### EFFECT OF TEMPERATURE

Temperature influences the electrical resistance of the nylon units. This influence, however, is comparatively moderate and, for practical purposes, could be ignored, especially where the temperature fluctuations are not too great. For careful research work, however, it is necessary to make temperature corrections. Figure 8 shows a method for making the necessary corrections.

Although the common liquid-expansion type of thermometer can be used to measure surface soil temperatures, three other types have been found more convenient for field use. Liquid electrical resistance thermometers (3) and

thermistors manufactured by the Western Electric Company are well adapted to deep installations. Both of these resistance-type thermometers are especially convenient because their resistance range falls within that of the Wheatstone

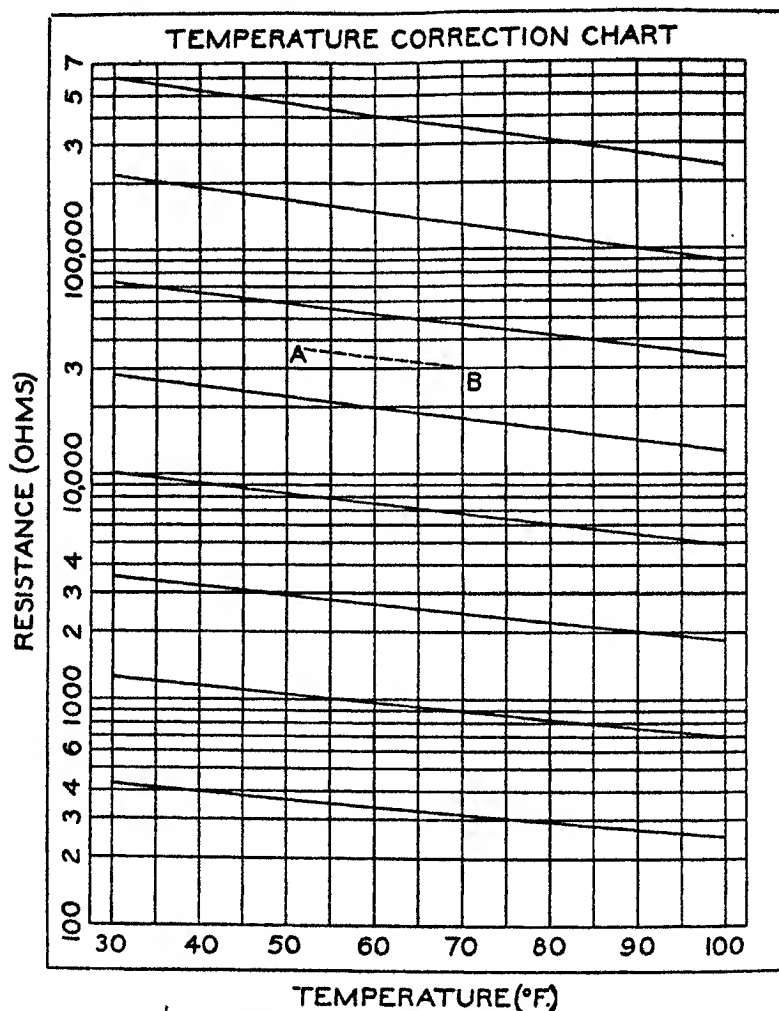


FIG. 8. TEMPERATURE CORRECTION FOR NYLON UNITS

A resistance reading of 38,000 ohms at 52°F. at A represents a resistance of 30,000 ohms at 70°F. at B.

bridge used to measure unit resistances. A bimetallic dial-indicating instrument offered by the Weston Company is useful for measuring temperatures at shallow depths and is much more rugged than conventional glass-stem thermometers.

#### DIRECTIONS FOR USE

For the most accurate determination of soil moisture, nylon units must be calibrated for each soil, and temperature corrections applied to each measure-

ment. Although directions for calibration have already been discussed, it is here emphasized that the following points must be closely observed:

1. An excess of water must be added to the soil when the units are calibrated. Not only must the sample be saturated, but there must be a thin film of excess water on top. This precaution ensures intimate contact between soil and absorbent surfaces.
2. Air trapped underneath the unit must be expelled by gentle pressure on the unit and by tapping the pan.
3. After the unit has been properly settled in the pan and water added, the pan is covered and allowed to stand for 5 to 10 hours to allow establishment of chemical and physical equilibriums.
4. For calibration purposes, nylon units should be equipped with flexible lead wires so that handling after equilibrium is established will not disturb the absorption unit or the sample. Clamping the leads to the pan assures that the unit will not be disturbed during subsequent manipulations.
5. It is recommended that calibration measurements be made on the second, rather than on the first, drying cycle. After every wetting, however, the air must be expelled from under the unit and the pan contents settled by gentle tapping.
6. Drying should not be hastened, but should be allowed to take place slowly.

When units are installed in the field, a 4-inch post-hole digger is employed. Small samples of various horizons are set aside for calibration purposes. At desired depths the bottom of the hole is tamped flat, and a unit, placed horizontally, is well firmed within the material of that particular horizon. It is advisable to place some loose soil on top of the tamped bottom before setting the unit. This will ensure better contact at the bottom. Then a small amount of soil is placed on the top of the unit and firmly tamped. This procedure is employed for every unit buried in the same hole.

#### SUMMARY AND CONCLUSIONS

A nylon electrical resistance unit developed for determining soil moisture in the field is described. It has internal electrodes similar in principle to those of plaster of paris blocks but radically different structural and absorbing material.

From all evidences thus far obtained, the nylon unit furnishes a very good method for measuring total soil moisture from saturation to almost air-dryness. It is reasonably accurate and is reliable and highly sensitive to moisture changes, especially at the high levels of water content where a sensitive method is most needed. It lends itself easily and conveniently to calibration. The unit should last more than 5 years in the soil. For these various reasons, the nylon electrical resistance method should be of value to highway engineers and hydrologists who are interested in measuring total water and, especially, water near the saturation point.

The method should also be of service to agronomists and plant physiologists, not only for measuring total soil moisture, but also for measuring available water content of soils. Although the soluble salt content of soils affects the nylon unit, the errors arising therefrom are not serious, especially when each soil is calibrated separately.

From the large number of soils thus far investigated it appears that for most soils, and especially agricultural soils, the saturation point lies at about 150 ohms

resistance, the field capacity in the vicinity of 2,500 ohms, and the wilting percentage at around 300,000 ohms. When soils contain only 50 per cent of their original total available water content, the electrical resistance is at about 40,000 ohms.

For the highway engineer and the hydrologist, who are interested mainly in determining total water content over a wide range, the nylon method is definitely superior to the plaster of paris method.

Even for the agronomist and the plant physiologist, who are interested mainly in determining the total available water content, the nylon method may also be superior to the plaster of paris method. Long and extensive use, however, has proved the plaster of paris method to be satisfactory in determining available water. Until further knowledge is obtained, the nylon method should be used largely to supplement the plaster of paris method, especially in very wet conditions where the gypsum block tends to disintegrate. Further agronomic investigations may justify replacement of the plaster of paris block method by the nylon method.

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# SOILS AND THEORY OF COLLOIDAL BEHAVIOR: I. INSOLUBLE ACIDS AND BASES

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Soil science had its birth at a time when colloids had caught the imagination of physical chemists, and the brilliant researches of Freundlich, Zigmondy, Ostwald, and others directed the attention of agriculturists to the scientific study of the soil, which bore a striking resemblance to other colloids. A good deal of ground was covered in a short time, and colloids began to dominate scientific literature on soils. There was much speculation and theorizing, all revolving round one central theme "adsorption."

## THE "ADSORPTION" CONCEPT

The theory of adsorption as applied to soils was at once a stimulus and a hindrance to the progress of soil science. By directing fruitful lines of thought into wrong channels, it failed to coordinate the divergence of views. Empirical methods of examining soils began to be advocated, and a sort of loose terminology sprang up in soil literature. We speak of "absorption capacity," "saturation capacity," "base-exchange capacity," and even "base-exchange content" without ascertaining whether they mean the same thing. For determining all these constants there are empirical methods which give different results, and the choice of one or the other method depends on the whim of the individual worker.

About a dozen-odd methods of finding lime requirements of soils still puzzle students of soil science; what is meant by "lime requirement" is not even known. Is it a fundamental constant of the soil or has it only a relative value with respect to plants? Some speak of a soil as "unsaturated" when there are no exchangeable bases; others like to refer to the same thing as "saturated with hydrogen ions." The nature of the soil colloids is so ill defined that in sheer desperation we have begun to refer to it as the "adsorption complex" or "exchange complex."

Most soil workers are gradually veering round to the view that soil acidity is due to insoluble acids ionized on the surface, with the H ions soluble in water but not parting company with the heavier portion of the complex, giving rise to a condition best described after Michaelis as "acidoid." An "acidoid" gives only a two-dimensional solution in water, and its quantity is limited by the monomolecular layer constituting the surface in actual contact with water. Purely in descriptive terminology the distinction between an acidoid and a true acid may be retained, but it should be emphasized that there is no fundamental difference between the two. A chemical reaction confined only to the surface is in no way different from molecular reaction in a homogeneous medium.

Chemical reactions in molecularly disperse systems take place in stoichiometric proportions. The proof of stoichiometry is generally lacking in surface reactions.

It is for this reason that colloid chemists prefer to retain the concept of adsorption in this connection, even admitting that the forces involved may be purely chemical such as chemical valencies. For instance, they would regard as adsorption even the formation of a film of silver chloride on a sheet of silver by the action of chlorine, and similarly, a film of oxide on a piece of metal, although admittedly formed by the operation of chemical valencies, is regarded as an "adsorption compound," because the chlorinated silver sheet or the oxidized piece of metal does not conform to a "stoichiometric composition" on the results of a bulk analysis. Colloid chemists are prepared to admit that with increasing dispersion this bulk composition would tend to coincide with the formula of a simple compound of stoichiometric composition, but until that value is reached, they conceive an infinite number of "adsorption compounds."

The argument however, is extremely fallacious. The bulk composition in this case has no meaning. The chlorinated silver sheet or the film of oxide merely indicates that the chemical reaction is confined to the molecules on the surface. If the surface film could be scraped off, not only would the reaction proceed further, but the composition of the scraped film would conform to the "stoichiometric composition."

A chemical reaction, if it stops short of completion, cannot be designated as "adsorption" merely on that account. An acid can be gradually neutralized with a base, yielding an infinite variety of intermediate compounds each having its own characteristic pH value, dissociation constant, and activity coefficient, before reaching the stoichiometric proportion, but we cannot call these products "adsorption compounds."

#### MOLECULAR VS. SURFACE REACTIONS

Molecular chemistry deals with reactions that have reached completion, resulting in a state of equilibrium throughout the mass of the reacting bodies. In surface chemistry, the active mass constitutes a monomolecular layer on the surface; the reaction stops because the product of the reaction forms an impenetrable film through which one of the reacting bodies cannot pass. The real difficulty in applying the law of mass action and stoichiometric proportion to these reactions lies in the determination of the active mass. As the active mass is not distributed throughout the entire bulk, but is confined only to the exposed surface, it must be determined indirectly. For instance, if an acid of unknown mass and molecular weight, presenting a large surface, is allowed to react with different bases, and if these bases are used up in equivalent proportions, the reaction is admittedly a simple chemical neutralization, and the active mass of the unknown acid is equivalent to the bases required for neutralization. Any attempt at designating this straightforward neutralization as "adsorption" is bound to lead to confusion, even if admittedly, the forces involved in adsorption are essentially chemical valencies.

The laws of classical chemistry as embodied in stoichiometric proportion are so well proved in molecular dispersions that they cannot be expected to fail in the case of surface reactions. There is no necessity for departing from the well-

established laws of chemical equivalence and resorting to adsorption, if we remember that the active mass in a disperse system may constitute only a limited proportion of the total mass uniformly spread over the entire surface.

Let us suppose that the surface of every solid is a two-dimensional molecular dispersion, and when the solid-air interface is replaced by the solid-liquid interface, the surface forms a true solution in the liquid, provided the contact angle is zero. The solution, no doubt, exists only at the interface and is confined to that portion of the liquid immediately in contact with the surface; nevertheless, this solution has a finite bulk and monomolecular thickness. Within this solution the molecules constituting the surface are in dynamic equilibrium with the molecules of the solvent so that the surface solution is perfectly homogeneous and behaves exactly like any other solution.

When a solid surface comes in contact with a liquid that can wet, it immediately dissolves. If the molecular forces of cohesion are stronger than the osmotic pressure of the surface solution, the surface molecules cannot diffuse out and the molecular solution is confined to the surface. If, on the other hand, osmotic forces are stronger than cohesion, the surface molecules diffuse out and the solution is no longer confined to the surface but the entire body of the liquid becomes one homogeneous molecular dispersion or true solution. It is emphasized, however, that the two solutions are fundamentally alike, and the difference, if any, is of degree and not of kind.

Acids are compounds of ionizable hydrogen which is capable of being replaced by metals, forming salts. Hydrogen, therefore, is an essential constituent of all acids. A part or all of this hydrogen may be present in the ionic state. The concentration of the ionized hydrogen in the solution of an acid determines its "strength" or "activity." In strong acids like  $\text{HCl}$  or  $\text{HNO}_3$ , the whole of the hydrogen may be present as ions. In a weak acid like acetic or boric, only a minute fraction (0.01 to 0.1 per cent) may be present in the ionic state.

The hydrogen-ion concentration of a pure solution of an acid is a fundamental constant and is related to the total hydrogen in the system in accordance with the law of mass action. A soil from which all the bases have been removed by acid treatment behaves like an acid. It is not soluble in water in the ordinary sense, but it gives a well-defined hydrogen-ion concentration capable of exact measurement. The system follows the law of mass action, and therefore the concentration of hydrogen ions is related to the total hydrogen in the system. Like molecular dispersions, it has a quantity as well as intensity factor. If the state of equilibrium is disturbed in any part of the system it would tend to equalize. Since the cations are fixed on the surface of the particles, their activity must be governed by the extent of their surface, for only the surface is in solution.

Since in all acids the equivalent concentration is reckoned with reference to hydrogen only, we can disregard the rest of the soil. Just as the normal solution of an acid contains 1 gram molecule of hydrogen per liter of the solution, so a soil suspension may be regarded as equivalent to a normal solution if 1 liter contains enough soil to give 1 gram molecule of hydrogen. The constitution of the rest of the soil does not interest us for the moment; we are concerned only

with the hydrogen, which is replaceable by a metal strictly in accordance with the classical definition of an acid. It must be understood that this hydrogen forms an integral part of the surface. It is not adsorbed on the surface, and therefore, cannot be removed without breaking up the molecular structure of the surface. It can, however, be replaced by any other cation as in true acids.

It must be remembered that "solubility" and "insolubility" are relative terms. An acid that is apparently insoluble can give appreciable amounts of hydrogen ions if it has a large surface in contact with water; moreover, these hydrogen ions

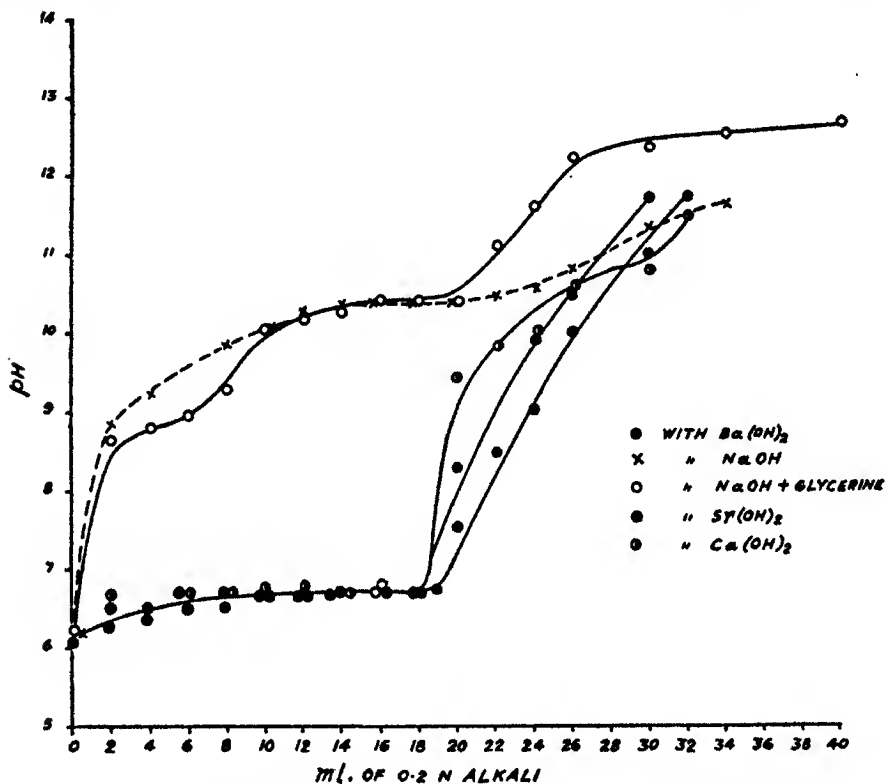


FIG. 1. TITRATION CURVES OF MOLECULAR STEARIC ACID WITH VARIOUS ALKALIES

are in equilibrium with the total hydrogen on the surface strictly in accordance with the law of mass action. If the area of this surface is increased, the concentration of the hydrogen ions increases, not in direct proportion to the increase in surface area but in proportion to the increase in the total acidity and the ionization constant of the acid. If the surface is doubled, the total acidity, no doubt, is doubled, but not the H-ion concentration. These hydrogen ions are actually in solution, though the substance as a whole is insoluble. Undoubtedly, they are carried along with the surface when the suspension is filtered, but they would have been carried along even with a soluble substance if the solute could be

separated from the solvent through a semipermeable membrane. In the hands of Svedberg, who designed a centrifuge giving 145,000 revolutions per minute, even the molecules of sodium chloride could be separated from solution, and of course Cl ions went along with Na ions. It must be borne in mind that the distinction between a true solution and a colloidal solution is merely one of degree and not one of kind and that there is no fundamental difference between a molecular solution and a surface solution. A dissolved body can be defined as that portion of a substance the molecules of which are in contact with the molecules of the solvent.

Let us take the case of a typical insoluble acid like stearic acid, which dissolves in alcohol but not in water. An alcoholic solution can, of course, be titrated. When the acid is put in water, however, it merely floats and would not combine with an alkali at ordinary temperature even on prolonged shaking. If the acid is dissolved in alcohol and the alcoholic solution is dropped in large excess of water in a thin stream and if the liquid is violently agitated just underneath the nozzle, the precipitated stearic acid comes out in a state of subdivision so fine that the particles are almost of molecular dimensions. The precipitated acid is still completely insoluble in water; it can be filtered and obtained as a bulky precipitate with a large amount of water held in the interstices. It can be washed with water over the funnel without application of suction. If a portion of the wet acid is titrated with  $\text{Ba}(\text{OH})_2$  solution, it yields a perfect titration curve with a well-defined inflection at the equivalent point, despite the fact that the acid is completely insoluble, as is its Ba salt. This molecularly dispersed acid behaves exactly like a soluble acid, and its titration curves with various alkalis show that it is entirely in a state of molecular dispersion (fig. 1). It can be titrated with  $\text{Ba}(\text{OH})_2$  solution, with phenolphthalein as indicator, and in every instance is found to have 100 per cent active mass.

#### FORMATION OF MOLECULAR STEARIC ACID

To study the conditions of formation of molecular stearic acid, a number of experiments were set up. The results are described in the following sections.

To determine whether the rate of addition of the alcoholic solution had any effect on the degree of dispersion attained by the precipitated stearic acid, the solution was added in varying lengths of time. The precipitated stearic acid was titrated with  $\text{Ba}(\text{OH})_2$ , with phenolphthalein as indicator. The results in table 1 show that stearic acid solution could be added as fast as possible without affecting the results.

To determine whether the amount of alcoholic solution of stearic acid added to water had any effect on the state of dispersion or active mass of the precipitated acid, different volumes of 1.7 per cent solution of stearic acid in alcohol were added to 500 ml. of water. The precipitated stearic acid was titrated with  $\text{Ba}(\text{OH})_2$  as before. The results (table 2) show that virtually all the precipitated acid is in molecular state with 100 per cent activeness. The low values in the case of smaller additions are partly due to slight spillage of the acid during the violent agitation to which the water is subjected during addition; this can cause

greater percentage error when the total quantity is small. Stearic acid solution in every case was added very rapidly.

As Ba-stearate is formed from stearic acid which is in molecular form, it was of interest to see whether this Ba could be precipitated as sulfate on addition of  $\text{H}_2\text{SO}_4$ , leaving behind stearic acid in the same state of dispersion. Molecular stearic acid was titrated with  $\text{Ba}(\text{OH})_2$ , and the Ba-stearate that was precipitated was again titrated with  $\text{H}_2\text{SO}_4$ .  $\text{BaSO}_4$  was precipitated quantitatively, leaving

TABLE 1

*Effect on dispersion of varying the rate of addition of stearic acid solution to water*

TIME OF ADDITION OF 50 ML. SOLUTION TO 600 ML. WATER	0.2 N $\text{Ba}(\text{OH})_2$ SOLUTION REQUIRED FOR COMPLETE NEUTRALIZATION
minutes	ml.
17	25.8
5	26.0
$1\frac{1}{2}$	25.9
$\frac{1}{2}$	25.9

TABLE 2

*Active mass in precipitated stearic acid when varying amounts of alcoholic solution are added to water*

ALCOHOLIC STEARIC ACID ADDED TO 500 ML. WATER	ACTIVE MASS
ml.	per cent
5	92.3
10	96.1
15	89.8
20	93.2
30	87.3
40	98.1
50	95.3
60	98.7
80	96.1
100	98.4
200	100
250	100
300	100

the stearic acid floating on the surface. This stearic acid was again titrated with  $\text{Ba}(\text{OH})_2$  and was found to be exactly similar to the original dispersed sample. This will be clear from the forward and back titration curves of the acid first with  $\text{Ba}(\text{OH})_2$ , then with  $\text{H}_2\text{SO}_4$ , and again with  $\text{Ba}(\text{OH})_2$  (fig. 2).

It is significant that the entire amount of Ba can be quantitatively precipitated as  $\text{BaSO}_4$  from Ba-stearate, which itself is insoluble. Stearic acid thus set free, though insoluble, can be separated from  $\text{BaSO}_4$  because it is lighter than water, whereas  $\text{BaSO}_4$  is heavier.

We have seen that the precipitated stearic acid from alcoholic solution, though insoluble, behaves in every way like a soluble acid in its reaction with alkalis. To test the possibility of reducing stearic acid to a fine state of subdivision, the following alternative methods were tried:

- (a) A hot alcoholic solution was gradually cooled with violent stirring.
- (b) A hot solution of stearic acid in benzene was gradually cooled with violent stirring.
- (c) Molten stearic acid, suspended in hot water, was gradually cooled with violent stirring.

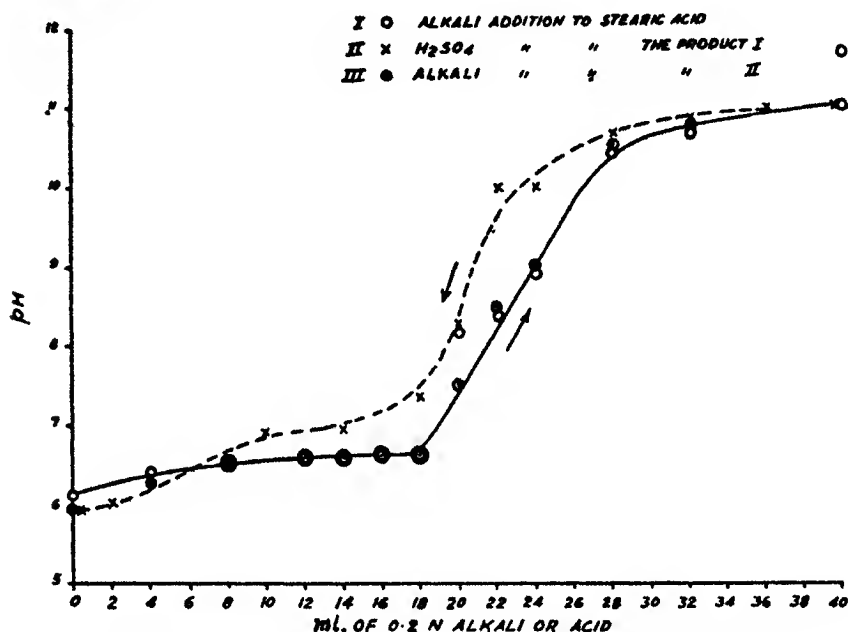


FIG. 2. FORWARD AND BACK TITRATION CURVES OF STEARIC ACID WITH  $Ba(OH)_2$  AND  $H_2SO_4$

Methods (a) and (b) gave bulk stearic acid which had no active mass. Method (c) gave molecular stearic acid exactly like that prepared from alcoholic solution, as shown by its titration curve with  $Ba(OH)_2$ , which was similar to curves I and III in figure 2, the point of inflection coinciding with the theoretical neutralization point.

The technique of preparing molecular stearic acid from hot water is as follows:

Molten stearic acid is run into hot water through a glass tube with a capillary end, which is held at the point of maximum stirring. The water is then allowed to cool gradually while the stirring is continued.

It is well known that the titration of boric acid with  $NaOH$  does not give a sharp point of inflection. When the titration is done in the presence of mannitol or glycerine, however, a sharp inflection at the neutral point is obtained<sup>1</sup>. It

<sup>1</sup> Britton, H. T. S. Hydrogen Ions—Their Determination in Pure and Industrial Chemistry. Chapman & Hall, Ltd., London. 1929.

was found that molecular stearic acid behaves in a similar way, that is, the point of inflection is sharper when titration with NaOH is conducted in the presence of 4 per cent glycerine (see figure 1).

The general similarity in behavior of molecular stearic acid and boric acid, one insoluble and the other soluble, leads to only one conclusion, that there is no fundamental difference between the two. It is the failure to recognize this essential similarity between the soluble and the insoluble, but surface-soluble, electrolytes that has given the so-called phenomenon of "adsorption" undue prominence.

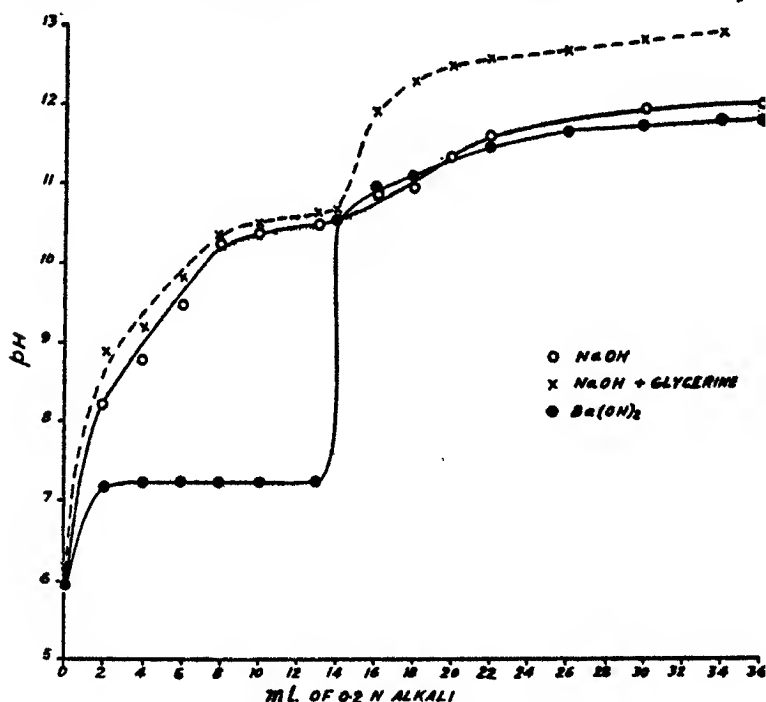


FIG. 3. TITRATION CURVES OF PALMITIC ACID

As expected, palmitic and myristic acids behave like stearic acid and can be prepared in the molecular state from their alcoholic solutions exactly in the same manner. The titration curves of these acids with various alkalis are shown in figures 3 and 4. In each case a perfect titration curve results with a sharp point of inflection. The effect of glycerine in making the point of inflection more prominent is also brought out. The method of dispersion appears to be of general application, and the distinction between a soluble and an insoluble acid narrows down to the state of aggregation. An acid which is insoluble behaves like a soluble one if it is dispersed sufficiently to make every molecule accessible to water molecules.

It might be pointed out that the results discussed so far cannot be ascribed to partial solubility (of the ordinary type) of these acids in water. The argument that more and more acid might be dissolved as the neutralization proceeds will



not hold, for the reaction proceeds very rapidly, exactly as if the entire quantity of the fatty acid were in solution.

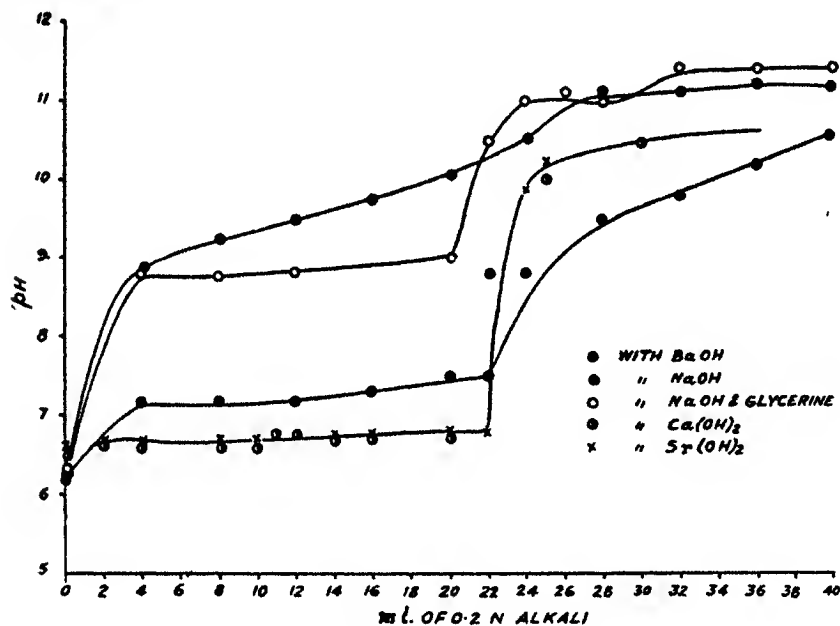


FIG. 4. TITRATION CURVES OF MYRISTIC ACID

TABLE 3

Relation between moisture content and "active mass" of stearic and palmitic acids  
Time of shaking with  $\text{Ba}(\text{OH})_2$ , 24 hours

STEARIC ACID		PALMITIC ACID	
Moisture	Active mass	Moisture	Active mass
<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
440.5	100.0	400.0	100.0
125.0	100.0	130.0	99.5
98.0	100.0	62.5	90.0
45.0	62.5	52.6	67.2
17.8	26.2	20.0	25.1
10.2	18.0	15.0	20.1
5.0	13.5	10.0	16.7
0	10.0	0	8.3

#### EFFECT OF DRYING AND AGING

Fine precipitates are known to undergo aggregation on aging. Molecular stearic acid in the wet state was kept for several days, and a weighed amount was neutralized with  $\text{Ba}(\text{OH})_2$  at varying intervals. The amount of  $\text{Ba}(\text{OH})_2$  taken up was the same in every case even after 15 days. The wet sample was then allowed to dry gradually, and at different moisture contents its reaction with  $\text{Ba}(\text{OH})_2$  was studied. The results given in table 3 show that the active mass

drops from 100 per cent to 10 per cent only when the moisture is reduced from 100 per cent to 0. The reduction in active mass began to take place at 90 per cent moisture content.

Experiments with palmitic acid gave almost identical results (table 3).

A sample of dry stearic acid was shaken for varying intervals up to 25 days to see whether by longer shaking more acid could be neutralized by  $\text{Ba}(\text{OH})_2$ . It was found that even when the sample was shaken for 25 days, the active mass did not exceed 10 per cent.

These results are extremely important in showing the part played by water in the development of intramolecular forces of cohesion. During the process of drying, as the water film recedes into minute capillaries and the radius of curvature becomes less and less, surface tension forces of greater and greater magnitude come into play, with the result that the particles are drawn together by a negative pressure from the inside. It is remarkable that this negative pressure is of sufficient magnitude to draw the particles so close to one another that molecular forces of attraction are exerted and intramolecular distances are so reduced that, on subsequent wetting, water molecules cannot get in between.

It might be mentioned, however, that the case of stearic and palmitic acids is rather different in that these fatty acids are not easily wetted by water. When they are first precipitated in the molecular state, all the molecules being in contact with water, the contact angle is 0. As the sample dries and aggregates are formed, even if the gaps thus created are not of molecular dimensions, water still cannot get into them. Thus, even if the active mass is there, it cannot come into play unless the solid air interface could be replaced by solid liquid interface.

It is interesting to note that the cohesive forces set up by the intracellular surface tension effects can be demonstrated for soils by measuring the effect of drying on their dispersion coefficient<sup>2</sup> or cohesion.<sup>3</sup>

Molecular aggregates of an acid may be so constituted as to leave gaps of sufficient magnitude that water molecules can penetrate the interstices. Such an acid, even if insoluble in water, might still give a perfect titration curve because of its surface solubility. A case in point is that of uric acid, which, though insoluble in water, can be titrated with  $\text{Ba}(\text{OH})_2$  even though Ba-urate is also insoluble. This is clear from figure 5, which shows the titration curve with  $\text{Ba}(\text{OH})_2$ . A 0.5-gm. sample of uric acid was dispersed in 600 ml. of water with constant stirring and titrated with 0.2 N  $\text{Ba}(\text{OH})_2$ . The acid, when titrated in this manner, shows approximately 75 per cent active mass, which rises to 100 per cent when the acid and alkali are shaken together for 24 hours. Maximum active mass is obtained only when excess alkali is shaken with the acid. The unreacted alkali is filtered off and determined. It is very likely that, on prolonged shaking with strong alkali, fresh surfaces that otherwise might not have been

<sup>2</sup> Puri, A. N., Keen, B. A. The dispersion of soil in water under various conditions. *Jour. Agr. Sci.* 15:147. 1925.

<sup>3</sup> Puri, A. N., Asghav, A. G., Dua, A. N. 1940 Physical characteristics of soils: VI. Influence of clay, exchangeable bases, and hygroscopic moisture on soil cohesion. *Soil Sci.* 49: 239.

accessible are exposed. It is also likely that a stronger solution may have greater wetting power to penetrate the minutest capillaries inaccessible to weaker solutions. The effect of glycerine on the titration curve with NaOH is also brought out in figure 5.

Silicic acid and aluminum hydroxide are two typical examples of insoluble acid and alkali with which we are particularly concerned in soils. An estimate of the active mass in freshly precipitated silica and alumina gel will throw considerable light on the nature of soil acidity and surface reactions. Silicic acid gel was prepared by addition of dilute HCl to sodium silicate under violent stirring. Alumina gel was prepared by addition of aluminum sulfate to ammonium hydroxide in the same apparatus. The gel in both cases was freed from salts by

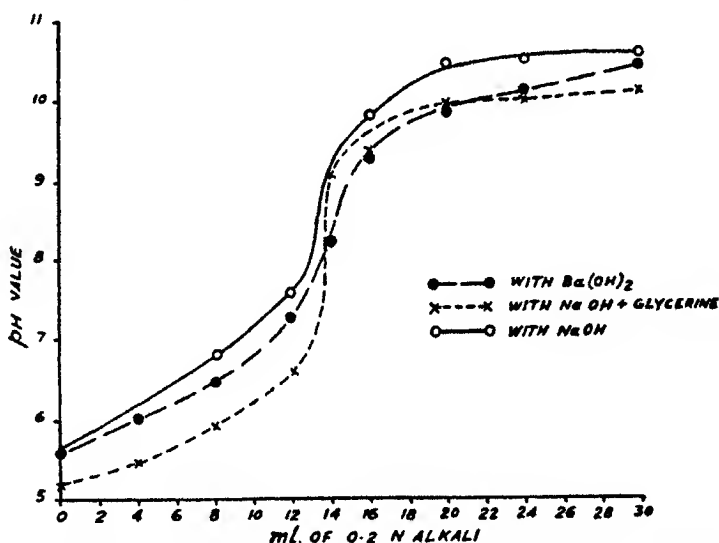


FIG. 5. TITRATION CURVES OF URIC ACID WITH  $\text{Ba}(\text{OH})_2$  AND WITH  $\text{NaOH}$  IN PRESENCE AND IN ABSENCE OF GLYCERINE

prolonged leaching with pure distilled water. During this process the gels were not allowed to dry. A portion of the wet sample was taken for titration, and a similar portion was taken for moisture estimation by drying at 100 to 110°C. The wet samples were shaken with excess of standard  $\text{Ba}(\text{OH})_2$  for varying lengths of time, at the end of which, the unreacted portion of the  $\text{Ba}(\text{OH})_2$  was determined. The amount of  $\text{Ba}(\text{OH})_2$  taken up by a known weight of dry silicic acid or alumina gave the active mass in the sample.

The amphoteric nature of alumina makes possible its estimation by reaction with either an acid or an alkali. The choice of an acid or an alkali that would give an insoluble salt is rather limited. Admittedly, Ba-aluminate has not been recognized as a possible salt of aluminic acid, but it is formed in equivalent proportions with the active mass of aluminum hydroxide. Since it is insoluble, it has escaped recognition. Active mass due to surface solubility, of course, can be found by reaction with a substance only if the end product is insoluble, other-

wise there is danger that fresh surfaces may become exposed and the reaction proceed to the end.

Gels of silicic acid and alumina dried to different degrees of moisture were shaken with  $\text{Ba}(\text{OH})_2$  solution for different lengths of time, and the amount of  $\text{Ba}(\text{OH})_2$  neutralized in every case was determined. The results in terms of the active mass in the various samples are given in tables 4 and 5.

The data show that when moisture content is at a level of several hundred per cent, drying of the sample leads to a reduction in active mass.

TABLE 4

*Relation of moisture content, time of shaking, and active mass of silicic acid*

TIME OF SHAKING	ACTIVE MASS* AT VARIOUS MOISTURE CONTENTS					
	785%	589%	426%	150%	38%	13%
days	%	%	%	%	%	%
1.....	61.5	61.5	61.5	50.0	10.2	4.2
2.....	75.2	61.5	61.5	50.0	10.2	5.8
4.....	75.2	66.2	66.0	60.0	20.4	7.2
8.....	—	77.4	68.0	68.0	32.2	10.0
10.....	90.0	77.4	77.0	68.0	38.0	10.0
15.....	90.0	90.0	90.0	75.2	50.0	15.0

\* 333.3 ml. of 0.1 *N* alkali per gram of silicic acid is taken as 100 per cent active mass.

TABLE 5

*Relation of moisture content, time of shaking, and active mass of alumina*

TIME OF SHAKING	ACTIVE MASS* AT VARIOUS MOISTURE CONTENTS								
	3409%	2148%	1624%	733%	450%	266%	150%	50%	22%
days	%	%	%	%	%	%	%	%	%
1.....	100	90	61.1	61.0	60.0	45.0	30.0	15.3	4.8
2.....	100	90	81.1	70.0	70.2	45.0	30.0	18.0	10.2
4.....	100	90	90.7	85.8	72.2	50.0	30.0	23.6	15.4
8.....	100	90.5	90.7	86.3	72.2	62.2	45.0	—	—
10.....	100	100	100	91.6	83.3	72.0	45.0	29.8	19.3
15.....	100	100	100	91.9	92.0	72.0	46.2	30.7	23.5

\* 360 ml. of 0.1 *N* alkali per gram of  $\text{Al}_2\text{O}_3$  is taken as 100 per cent active mass.

It was found that aging as such had no effect on these gels. Freshly precipitated silicic acid and alumina gels were kept for a month with large excess of water without any effect on the active mass, which remained at 100 per cent. It is only when the moisture is reduced below a certain level that the effect of drying shows itself in a reduction in the active mass. It will be seen that the results are similar to those obtained with stearic or palmitic acid (cf. table 3), and the phenomenon appears to be of universal application. It is interesting to note that what is known as aging in colloid chemistry may be merely a manifestation of drying.

It is clear from the foregoing that the behavior of both silicic acid and alumina, two of the most important constituents of soils, is capable of a very simple explanation based on well-known laws of chemical equivalence in which so-called "adsorption" has no place at all. It is significant that, even with freshly precipitated gels, whatever the concentration of  $\text{Ba}(\text{OH})_2$  and whatever the time of shaking, the theoretical amount (corresponding to 100 per cent active mass) is never exceeded. The time of shaking or the concentration of  $\text{Ba}(\text{OH})_2$  has some effect when, because of aggregation, the active mass is less than 100. It is understood that the cohesive forces coming into play during the process of drying will depend on the size of the capillaries and the chance association of the particles. These cohesive forces will naturally vary at different stages of drying; and surfaces that are not exposed might become so on shaking for longer periods. It is, therefore, characteristic of all silicates and soils that their reaction with alkalis proceeds very slowly after the initial neutralization, which is very rapid. In a freshly precipitated silicate, however, when the active mass is 100 per cent and the particles have not formed aggregates, the reaction is instantaneous, as if the entire mass were in solution. The speed of reaction between an alkali and dried silicic acid must depend on the strength of the alkali. This is an inherent error in the determination of the titration curves of such substances. The titration curves must undergo a twist, for all points may not refer to the same active mass. At higher concentrations of alkali some extra surfaces might be exposed which were not operative at lower concentrations. Indeed, it is not certain that the entire active mass may not react, provided the alkali is strong enough and the time of shaking is very long. It is seen that, with soils, a state of equilibrium is not reached even in 3 months. Thus we may have to make some distinction between the active mass that is in surface solution and the active mass that can be brought into solution. The distinction, however, is no greater than might be made between the portion of a substance actually in solution and that still in the solid state but which can be brought into solution on prolonged shaking. It is the slow accessibility of the microcapillaries to the reacting fluid which is the cause of the slow rate of reaction, and the end of the reaction cannot be predicted unless we know the total amount of the active mass free as well as inaccessible. The profound influence of moisture content on silica and alumina is worthy of note. It is hardly logical for us to designate the reaction of silica and alumina with alkalis as purely chemical neutralization when the moisture content is high and the active mass is 100 per cent, and to bring in "adsorption" as soon as these substances are dried and the active mass is lowered by aggregation.

#### CONCLUSIONS

Insoluble acids like stearic, palmitic, myristic, and silicic, as well as silicates and aluminum hydroxide, can be obtained in a state of molecular dispersion. Though filtrable, the precipitates react with alkalis instantaneously in stoichiometric proportions. These substances thus precipitated may be said to have 100 per cent active mass, with a moisture content ranging from 100 per cent in

the case of stearic acid to as much as 2,000 per cent in the case of aluminum hydroxide.

When the moisture content of these precipitates is reduced below a certain critical value, intramolecular cohesive forces come into play and aggregates are formed, resulting in a reduction in the exposed surface and consequently the active mass. Thus, when the moisture content is reduced to a state corresponding to almost dryness, the active mass is reduced to 5 or 10 per cent or even to 0.

The relation between moisture content and active mass is perfectly smooth and is susceptible of a simple explanation which makes it quite unnecessary to bring in the phenomenon of "adsorption," whatever meaning might be attached to this vague but all comprehensive term.

## BOOKS

*Conservation in the United States.* Third Edition. By A. F. GUSTAFSON, C. H. GUISE, W. J. HAMILTON, JR., AND H. RIES. Comstock Publishing Company, Ithaca, New York, 1949. Pp. 534, figs. 254. Price \$5.

The authors of this book are professors of soil technology, forestry, zoology, and geology, respectively, at Cornell University, and they deal with the subject of conservation from these four points of view. The several chapters are concerned with the development of the idea of conservation, the nature and use of soil, water and its conservation, soil depletion and erosion, soil conservation, forestry, forest conservation, parks, grazing lands, fish and fisheries, game and fur resources, other useful wildlife, mineral resources, metals, coal, petroleum and natural gas, and the nonmetallic elements. The subject is interestingly presented, with excellent graphic and photographic illustrations. The part of the book that deals with mineral resources could be considerably expanded to advantage. Reference is made to the publications of some 170 authors. The book merits a place on the shelf of everyone interested in the conservation of our natural resources.

*Isotopic Carbon.* By MELVIN CALVIN, CHARLES HEIDELBERGER, JAMES C. REID, BERT M. TOLBERT, PETER E. YANKWICH. John Wiley & Sons, Inc., New York, 1949. Pp. 376, figs. 107. Price \$5.50.

This book comes at a very opportune time. It deals with the production and properties of isotopic carbon, measurement of carbon 13, carbon tracer radiations, instruments, detectors, sample preparations, vacuum techniques, synthesis of carbon-labeled compounds, criteria of purity, degradation procedures, and biosynthetic methods. An extended appendix gives dilution methods, statistical procedures, coincidence corrections, counter efficiency, self-absorption data for barium carbonate and wax, examples of assay operations, flow in vacuum systems, gauges and manometers, and an induction stirrer for use in closed systems. Every synthesis with isotopes that had been reported up to the time of writing the book is described. A bibliography of some 160 titles is appended, and reference is made to the work of some 600 authors. The writers of the book are all members of the scientific staff of the radiation laboratory at the University of California at Berkeley. The book is an excellent reference and would be a very helpful guide in undertaking work in this field of research. The diagrams of the apparatus employed are exceptionally good. The book is certain to enjoy a very wide reading.

*Plant Ecology.* Fourth Edition. By W. B. McDougall. Lea and Febiger, Philadelphia, 1949. Pp. 234, figs. 118. Price \$4.

Fundamental thinking on ecology has not been materially changed since the author's first edition appeared a good many years ago. The fourth edition of this very interesting book is much like the original, but, of course, some changes

have had to be made to bring it up to date. The several chapters deal with roots, stems, leaves, symbiosis, pollination, light, heat, air, soil, water, growth habits, plant communities, plant succession, phenology, and applied ecology. The illustrations are excellent. A list of pertinent references is appended to each chapter, and the appendix offers suggestions for the teacher of ecology. Anyone concerned with soil-plant relationships will find a great deal of thought-stimulating material in this book.

*Principles of Petroleum Geology.* By CECIL G. LALICKER. Appleton-Century Croft, Inc., New York, 1948. Pp. 377, figs. 157. Price \$5.

The first petroleum geologist was employed in 1897; the science of petroleum prospecting, therefore, is only about 50 years old. More than half of the oil produced in the world comes from rocks of tertiary age. About 31 per cent of the proved oil reserves are in the United States. The organic theory of the origin of petroleum is now generally accepted by scientists, and complex compounds of a nonfatty nature and low in oxygen are the most likely source of petroleum. These and many other very interesting points are developed in this volume. In addition, the whole field of petroleum geology, including the methods employed in discovering new fields, is covered in a comprehensive manner. The book will be of great interest not only to geologists and to those concerned with petroleum but to soil-plant scientists as well.

*Vernalization and Photoperiodism.* By A. E. MURNEEK AND R. O. WHYTE, with the cooperation of 14 others. Chronica Botanica Co., Waltham, Massachusetts, and Stechert-Hafner, New York, 1949. Pp. 196, plates 12. Price, paper-bound, \$4.50.

This is a symposium dealing with the history and development of our present concepts on the effects of chilling of germinating seeds and of length of day on mature plants, in relation to flowering and fruiting. Special consideration is given to the work of Georg Klebs, Nikolaj Maximov, Gustav Gassner, H. A. Allard, W. W. Garner, Anton Blaauw, Nikolaj Cholodny, and T. D. Lysenko, but reference is also made to the work of some 350 other research specialists in one or another phase of these fields of study. It is of interest to note that an estimated ten million acres of land in Russia were sown with vernalized seed in 1937. The extent to which control of light in relation to photoperiodism has been applied in practice is not indicated. The book presents a highly interesting picture of research developments in these subjects and is a very important contribution to the literature on them.

THE EDITORS.



# GENERAL FEATURES OF THE SOILS OF GREECE

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Greece is a narrow peninsula. No part of it is more than 100 miles from the seashore. Only 8 per cent of the surface of the country is 50 to 100 miles from the shore; and only 20 per cent, 25 to 50 miles. In other words, 72 per cent of the land is less than 25 miles from the seashore. This has a tremendous influence on the kinds of soils that are formed, in that it prevents the formation of great rivers and their deteriorating effects on the soil.

Greece, as illustrated in table 1, is a mountainous country. Of the entire surface of 32 million acres, only 11 million are at an altitude of less than 700 feet.

As a consequence of the combined influence of the narrowness and the mountainous character of the country, very large quantities of eroded materials are not deposited on the surface of the land, but, instead, are carried out to sea.

## SOIL-FORMING FACTORS

The principal factors, that is, climate, parent material, vegetation, and topography, that contribute to the formation of the soil of Greece might be described for the nonmountainous portion as follows:

The climate, a characteristic Mediterranean type, is mild, with a relatively wet winter that is succeeded by a hot and dry summer. The rainfall, concentrated in the winter, is generally rather limited. The mean annual precipitation of 59 meteorological stations is 28.6 inches. It fluctuates, according to location, between 8 and 52 inches. The average does not give a clear idea of the low effective value of the rainfall, however, because of the highly disadvantageous distribution of the precipitation during the year (fig. 1). The virtual lack of rainfall during the hottest months has important consequences upon soil formation, control of erosion, type of farming, and importance of irrigation. Furthermore,

<sup>1</sup> In preparing this paper, the writer has drawn freely on the following publications, to the authors of which he is greatly indebted:

EVELPIDI, C. *The Agriculture of Greece*. Athens. 1944.

KATAKOZINOS, D. The lateritic soils of Bermion Mountain. *Chem. Ann. [Athens]*. 1938; Is Greece of Today Viable?. Athens. 1946.

LIATSIKA, N. *General Soil Map of Greece*. Athens. 1942.

MARIOLOPOULOS, H. G. *The Climate of Greece*. Athens. 1938.

MINISTRY OF AGRICULTURE. *Forest Map of Greece*. Athens. 1947.

NEVROS, K. I., AND ZVORYKIN, I. A. Investigations of red soils of Attica, Greece. *Soil Sci.* 41: 397-415. 1936.

PAPOUTSOPOULOS, I. J., AND ZVORYKIN, J. Investigation on the soils of the Larissa area. Ministry of Agriculture, Athens. 1936.

TSOUMI, J. *The Agricultural Systems of Greece*. Athens. 1936.

ZVORYKIN, J. *Soil Maps of Crete, Evia, and Zante*, Athens.

ZVORYKIN, J., AND VRISSINDJI. *Soil Map of Thessaly*. Athens. 1947.

the low effective value of the precipitation is influenced by its form. Notwithstanding the serious lack of meteorological data, it can be said positively that the average precipitation per minute during the rains is very high and that torrential rainfall is common over most of Greece. Finally, rainfall distribution is very uneven. Only in the northern part of the country and on the mountains does snow have any practical significance.

The average temperature of 33 stations in Greece is  $16.9^{\circ}\text{C}$ . Here, also, large differences exist from place to place, because of the relatively great length of the country from north to south and the mountainous relief of the land.

The temperature falls from south to north. The rainfall drops from west to east. This is unlike other parts of Europe and Asia and is the reverse of North America, where the rainfall drops from east to west. This distribution of rain-

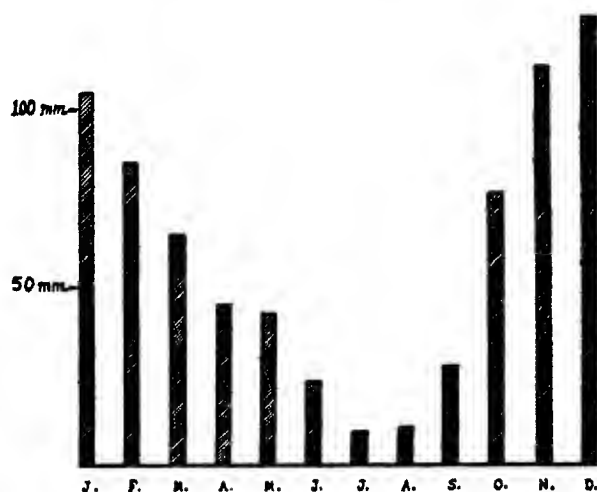


FIG. 1. MONTHLY DISTRIBUTION OF MEAN ANNUAL PRECIPITATION IN GREECE  
Average of 59 meteorological stations

fall, making the western part of Greece much more humid than the eastern, is mainly due to the direction of the principal mountains. All important Greek mountains run from north to south. During winter, the rainy season, the anticyclon of the Atlantic is extended as far as North Africa and produces north-easterly warm winds in the Mediterranean Sea. When these winds cross the Mediterranean, their humidity increases. The difference in temperature between North Africa and Greece is enough to bring the saturation point to a low level. When these winds meet the west coast of Greece and the mountains, a relatively rainy and humid environment results. A humid environment is formed, therefore, on the west slopes and tops of these mountains, but when the winds pass them and move across the eastern part of Greece, they are relatively dry.

The high atmospheric temperature of Greece results in rapid evaporation. Low rainfall and rapid evaporation give a low rainfall:evaporation ratio. Figure 2 gives an approximate idea of the distribution of this ratio.

Most of the soils of Greece can be arranged in two categories. In the first of these, the parent materials are of limestone origin, and in the second, they are from other kinds of rocks. Limestone contributes to the formation of two litho-genetic soils, terra rosa and rendzina. These are among the most widespread in the country. A further division of limestone into hard (crystalline) and soft (amorphous) has additional significance. Under the conditions of the dry, hot climate of Greece, hard limestone is, to a great extent, responsible for the formation of terra rosa, whereas soft limestone is responsible for the formation of rend-

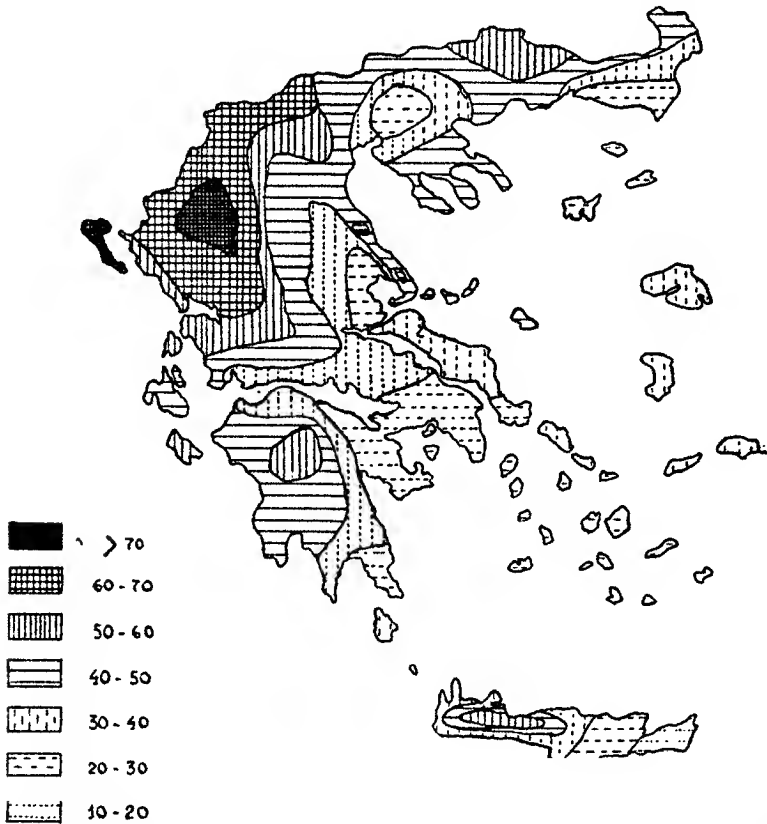


FIG. 2. DISTRIBUTION OF THE RAINFALL-TEMPERATURE RATIO IN GREECE

zina. Figure 3 gives an idea of the division of parent material of Greece into three main groups, limestone, nonlimestone rocks, and alluvial materials.

The dominant vegetative cover of Greece is trees, in spite of the fact that now only 15 per cent of the land is covered by forests. The type of forest vegetation varies widely according to latitude and altitude. The most widespread trees are chapean pines, black pines, firs, chestnuts, oaks, and beeches.

Because of the steepness of the slopes, the topography of the land plays an outstanding role in the formation and development of the Greek soils. Very steep and steep topography is much more frequent than are the flat and gently

undulating types. Of the 130 square kilometers in Greece, only 12, or less than 10 per cent, have a flat or slightly rolling topography. Table 1, dividing the land according to its altitude, gives a rough idea of the steep character of most of the land. This topography should always be borne in mind in the study of soil development, especially in relation to the erosion of the upland and to the alluvial deposits on the plains.



FIG. 3. DISTRIBUTION OF SOIL PARENT MATERIALS IN GREECE

#### METEOROLOGICAL BELTS

The great variation in altitude results in very different climatic environments and gives an excellent opportunity for study of many kinds of soils in a small area. Obviously, the soils should exhibit vertical differentiation. It is useful, therefore, to examine, separately, the highlands and the lowlands of Greece.

In the mountainous part, the influence of altitude on the climate outstrips by far the influence of geographic position and that of the great air currents. In the lowlands, the geographic position and the great air currents of the European continent, Asia Minor, and the Mediterranean Sea mainly influence the climate.

The mountainous part of Greece can be divided into four climatic belts, forming four corresponding belts of plant growth (fig. 4). The first is an alpine belt.

This has an altitude of about 2,000 meters. Its characteristic feature is its low temperature. The average annual temperature is 2° C., but the average annual

TABLE 1  
*Altitude of Greece above sea level*

LAND CLASSES	ALTITUDE	AREA
	m.	sq. km.
I.....	0- 200	44
II.....	201- 500	34
III.....	501-1000	36
IV.....	1001-1500	12
V.....	1501 and above	4
		130

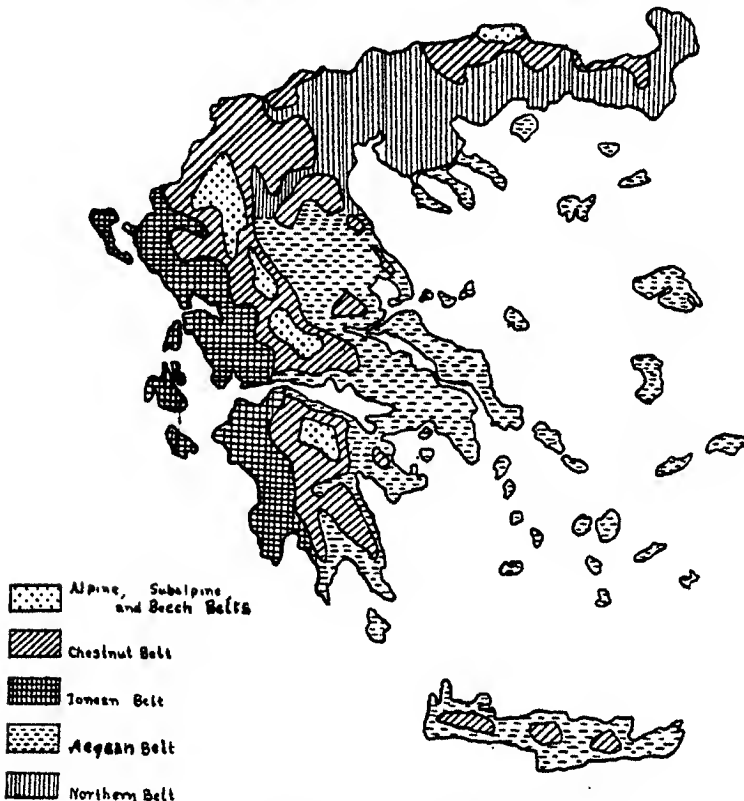


FIG. 4. METEROLOGICAL BELTS OF GREECE

minimum temperature is -40° C. Since the average temperature of May, June, July, and August is lower than 10° C., the growth of trees is prevented. The second mountainous belt is a subalpine one. Its altitude is between 1,500 and 2,000 meters. The temperature of this belt is more moderate than that of the

alpine belt, but it continues to be low enough to arrest the growth of trees. The third belt has an altitude between 700 and 1,500 meters. It can be called the belt of beeches. The average annual temperature is between 6° and 10° C. The average temperature from May to August is between 12° and 18° C., and the average annual precipitation is between 800 and 1,200 mm. (31-47 inches). A fairly abundant growth of firs, beeches, and black pines is normal for this belt. The fourth belt lies between 500 and 1,000 meters. It is characterized by an average annual temperature of 12 to 17° C., a mean minimum temperature of -10° C., and an average temperature from May to August of 20-30° C. It might be called the chestnut belt. Oaks and chestnuts are the predominant trees, although many other kinds are found in its deciduous forest growth.

The land lying at an altitude lower than 700 meters might be grouped into three other belts. Chalepean pine is a very common forest tree. The meteorological features of these belts were described in the beginning of the article. These three belts of the lowland might be defined as follows: First is the Aegean

TABLE 2  
*Meteorological belts of Greece*

BELTS	ALTITUDE	AREA
	<i>m.</i>	<i>sq. km.</i>
<i>Group A—mountainous belts</i>		
1. Alpine belt	2,000 and above	1
2. Subalpine belt	1,500-2,000	3
3. Beech belt	700-1,500	15
4. Chestnut belt	500-1,000	25
<i>Group B—low belts</i>		
5. Aegean belt	0- 700	43
6. Ionean belt	0- 700	18
7. Northern belt	0- 600	25
		—
		130

belt, which includes the southern part of eastern Greece. It is characterized by high temperatures and low precipitation. The mean temperature is higher than 17° C. and the mean precipitation is lower than 600 mm. (24 inches). The second is the Ionean belt, which includes the west coasts of Greece and the Ionean Islands. It is characterized by an equally high temperature but relatively high precipitation. The temperature is higher than 18° C., and the precipitation is higher than 800 mm. The environment is humid and subtropical. The third, or northern belt, includes the northern part of Greece. It is characterized by a temperature lower than 17 to 18° C. and a precipitation higher than 600 mm. The climate of this area lies between the Mediterranean and the Middle European. Figure 4 shows the meteorological divisions of Greece and table 2 approximate information about the land areas occupied by the seven belts mentioned above.

## PREDOMINANT SOIL-FORMATION PROCESSES

Let us now consider the predominant soil-formation processes that take place in light of the above features of climate, parent material, vegetation, and topography of the principal belts of Greece.

Greek soils, as a whole, are low in humus. As a result of the lack of rain during summer, plant life is of practical importance in the accumulation of humus only in winter. But even during this rainy part of the year, humus forms very slowly. Then, during the hot and dry summer, the small quantity of humus accumulated during the winter is decomposed to a very high degree. Consequently, because of the meteorological conditions prevailing in summer, it is very difficult for both Nature and man to build a high organic content in the soil. This lack of humus is dominant in Greek soils despite local conditions that allow formation, in some places, of soils with a relatively high content of organic matter. As a result of their impotence to build organic matter, the soils also have a low nitrogen content.

Physical types of weathering of the rocks prevail over chemical weathering. This is more pronounced in the dry Aegean belt, but it also applies to the wetter Ionian belt. In many places in the northern low belt, an equilibrium between the two processes is observable. In the chestnut belt, chemical decomposition gains the ascendancy but, in most cases, the fast removal of the weathering materials by erosion does not permit chemical reactions to imprint their effects upon the soil.

The formation of sand and silt fractions in the soil is much faster than that of clay. This is most pronounced in the Aegean belt, but it is important in the other belts as well. Few of the heavy clay soils of the country have been formed in place; most of them have been laid down as alluvial deposits, as the flood waters were compelled by their lowering velocity to drop their suspensions. Some of these alluvial clay soils were formed during ancient times, and some are of recent development. As the clay content of the soils is positively correlated with an increase in precipitation and temperature, a question arises as to which of these positive influences is dominant in Greece, where low precipitation and a high temperature occur simultaneously. In the Aegean belt, the effects of the low precipitation by far outweigh the effects of the high temperature. In the Ionian and northern belts, where the precipitation is two to three times as high as that in many places of the Aegean belt, the temperature is only a little lower. It is obvious, therefore, that in these belts the restraining influence of low precipitation on the formation of clay is fading. And, in spite of the fact that the rate of formation of clay in neither of these two belts is high, the combination of relatively high temperature and precipitation has brought in light soils, with a relatively high content of clay.

Leaching is not intensive. Under conditions of high evaporation and low rainfall, the upward movement of salts predominates in many places. In these places, the petrographical and chemical features of the parent materials continue to exist, even in the soils that have reached a high level of maturity. In the dry

Aegean belt, neither the monovalent nor the divalent bases are leached intensively. This slow leaching, and sometimes the lack of it, produce an accumulation of salts in the upper layers and, consequently, an alkaline reaction. The average pH of the soils in this belt is between 7.5 and 8. To the west and north, that is, in the Ionean and northern belts, a more intensive leaching takes place, and the monovalent bases are usually leached. In parent materials that are low in calcium, an acid reaction is developing.

Distinctive horizons of eluviation and illuviation are not formed very easily. This can be explained as a consequence of the combined influence of the slow and interrupted downward movement of water, which often reaches a point where the upward movement has the ascendancy over the downward; the low content of organic matter; the difficulties of stratification of the soil particles according to their size, owing to the low percolation of water; and the predominance of disintegration over chemical decomposition. The net result is that the majority of Greek soils have only A and C horizons.

Since the clay and organic matter content of Greek soils is low, their exchange capacity is also generally low. This is especially true of the Aegean belt. In that belt, the exchangeable cations are the monovalent bases. Scarcely any exchangeable H is found. In the northern and Ionean belts, a simultaneous increase of exchange capacity and of exchangeable H occurs. The exchangeable H very seldom reaches 5 or 10 per cent of the total exchange capacity. It should be remembered that in soils derived from parent materials that are rich in calcium, an increase in exchangeable H is hampered.

As a result of the combined influence of the high content of Ca in the parent material and the inadequate leaching, especially from the deeper soil layers, many Greek soils tend to form a lime horizon (pedocal). This has a pronounced influence on the circulation of ground water.

Erosion is working very intensively. This is the result of the loose structure of the soils, which, in turn, is determined by the low content of organic matter, clay, colloids, and moisture; the steep topography of vast areas; the torrential nature of the rainfall; and the narrowness of the country.

#### THE MAIN SOIL GROUPS

Pedological studies of Greece, as well as of other Mediterranean areas, have not reached a point where a comprehensive classification of their soils can be made. Glinka and Marbut have classified the soils of the north Mediterranean coasts, including Greek soils, as lateritic. In the low belts of Greece, a lateritic evolution has taken place. Passing over, for the moment, the mountainous belts, let us see what has happened in the low belts.

Lateritic evolution is best defined in the Ionean belt, where relatively high rainfall (between 800 and 1,300 mm.) is accompanied by high temperatures (between 18 and 20° C.). The external and microscopic characteristics of the soils of the area suggest such evolution. Rapid decomposition and disintegration of the parent material have been accompanied by development of a distinctive red color in many soils and a low content of organic matter. Such chemical



analyses of the soils as are available, however, fail to support the concept of a lateritic evolution. Before a definite conclusion can be reached about the nature of the soils of this belt, it is necessary to clarify the rate of separation of sesquioxides from silicates, the rate of removal of  $\text{SiO}_2$ , and the rate of fixation of Fe and Al. Are these three rates high enough to indicate that the corresponding processes are working intensively and giving birth to lateritic soils? Chemical analyses covering these problems are not only very few and very incomplete but they rarely give data about all the horizons and the underlying parent materials. Only comparison of the value of each constituent in every horizon with the parent material will indicate the removal or the fixation of each constituent.

The usual method applied to the pedological analysis of Greek soils has been that of Gedroiz, which does not use total analysis but, rather, that of the extract of the soil with 5 per cent KOH. The theoretical foundation of the Gedroiz method is based upon two assumptions: First, that a 5 per cent KOH extract gives the active part of the  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  that participate in the formation of kaolin; this should be the amorphous part of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  of the aluminosilicate complexes of the soils. Second, that when the analysis of the extract shows more  $\text{Al}_2\text{O}_3$  than is necessary for formation of kaolin, the soil is lateritic, whereas, when the analysis presents an  $\text{Al}_2\text{O}_3:\text{SiO}_2$  ratio equal to or lower than that of kaolin (about 1:1.18), there is a strong indication that the soil is podzolic.

It is not the purpose of this article to evaluate this method critically, but whether the content of the amorphous part of the aluminosilicates can serve as a decisive indication for use in the characterization of soils is undoubtedly a question open to further experimentation and discussion. In soils such as those of Greece, the movement and the fixation of  $\text{Fe}_2\text{O}_3$  have great significance in some places and may be greater than the movement and the fixation of  $\text{Al}_2\text{O}_3$ . For all these reasons, the author believes that, for the time being, the total analysis of soils affords the most reliable clue to the characterization of the movement and fixation of soil constituents.

Most of the few existing total analyses show an  $\text{SiO}_2:\text{R}_2\text{O}_3$  ratio between 2 and 2.5. The same values obtain in the clay. These values might give an impression that we are dealing with sialitic soils. Notwithstanding that only through comparison with the parent material can a reliable conclusion be reached, these values are an indication that  $\text{R}_2\text{O}_3$  is being removed faster than  $\text{SiO}_2$ . Nevertheless, some total analyses show lower  $\text{SiO}_2:\text{R}_2\text{O}_3$  ratios—between 1.5 and 2—, which indicates that the rate of release and removal of  $\text{SiO}_2$  from the aluminosilicates is faster and that the soils are at least tending toward laterites.

Before we attempt to explain the contradiction between the lateritic appearance of many soils and the high  $\text{SiO}_2:\text{R}_2\text{O}_3$  ratios, let us bear in mind two facts: First, in the majority of cases, the analyses were made on old cultivated lands, deprived from time immemorial of their native vegetation, and therefore the results do not present a clear indication of the natural evolution of the soils. The percolation of water and, consequently, the leaching are very different and usually much weaker in the cultivated land than in virgin soils covered by native, especially forest, vegetation. Second, many analyses were made upon semi-

eroded or alluvial materials and, consequently, the natural development of the soils has probably been distorted. The clue to the above contradiction probably lies in the calcareous nature of most Greek rocks and the high lime content of the resulting soils. It is possible that the role of lime in the soil-formation processes is much more important than has generally been accepted. A clear lateritic evolution of Greek soils, at least in the Ionean belt, is very probably prevented because of the high calcium content of these soils.

If the above assumption proves correct, then we should reach the conclusion that, in the not very dry calcareous soils, decomposition of the nuclei of aluminosilicate and removal of silica are going on very slowly. This is not because the climate does not permit rapid decomposition but, rather, because the intensive circulation of calcium gives a high degree of stability to the nuclei. Comparative analyses of many calcium-rich and calcium-poor soils would throw light on this subject. For the time being, we consider it enough to mention the following data from a region where parallel analyses are available. In the northeastern part of Greece there are large areas in which the soil is derived from non-calcareous parent material. We shall see that brown forest soils are formed there under the influence of the colder climate. Available analyses of the profiles of these soils indicate that the average  $\text{SiO}_2:\text{R}_2\text{O}_3$  ratio of the A horizon is 1.68, that of the B is 1.64, and that of the C is 1.79, whereas the corresponding relationships in neighboring calcareous soils, under similar climate, are between 2.2 and 3.

In wide areas of Greece, where the parent material is limestone, there is a clear divergence from the climatic zonation. Two principal interzonal groups of soils are formed from this divergence. Where the parent material is of hard limestone origin, the development is toward terra rosa. Where the calcareous parent material is soft limestone, the development is toward rendzina soils.

In the Aegean belt, because of the low rainfall and leaching, the removal of Si is much slower than in the Ionean belt, even under conditions of a lack of calcium. As a result of this low leaching, even "mature" soils tend to retain the petrographical and chemical composition of the parent materials. In soils of the Aegean belt derived from calcareous parent material, the same divergence from the climatic zonation toward terra rosa and rendzina is met. In the northern belt the rate of lateritic development is further retarded, and processes related to colder climates are sometimes met. But even here the calcareous parent materials continue to divert the zonal soils toward terra rosa and rendzina.

Where calcareous parent materials do not play a prominent role and interzonal soils are not formed, soil-formation processes give birth to the following zonal groups of soils: In the Aegean and Ionean low belts, and even in some parts of the northern belt, the soils formed can be classified as Mediterranean forest soils. This group of soils can be divided into two categories. In the Aegean belt, because of the intense upward movement of water and the low precipitation, the soils do not usually form horizons of eluviation. They have only A and C horizons. These soils may be called dry Mediterranean forest soils. They are alkaline in reaction and their laterization is very slow. In the Ionean low belt,

and in some parts of the chestnut belt, where the precipitation is high, horizons of eluviation are formed with more or less definite structure. The eluvial horizons usually have a red-chestnut color. The soils, and especially their B horizons, are often acid. It may be assumed that laterization takes place. This, group, again, may be called Mediterranean forest soils.

The soils formed upon the noncalcareous parent materials in the northern low belt might be classified as chestnut and gray forest soils. Laterization, if any, is very slow. The soils are very often acid and are seldom saturated with bases. In some parts of the mountainous belts of south and central Greece, such soils are developing. In parts of the main plains, where the influence of the sea and the mountains is diminishing, soils with steppe features apparently are developing. These are in forest areas, and the lack of trees is due to the action of man. The steppe features are not the result of natural evolution and, consequently, cannot be considered as genuine from the pedological point of view. These soils are very often acid and seldom are saturated with bases.

TABLE 3  
*Classification of Greek soils*

BELTS	PARENT MATERIAL		
	Poor in calcium	Hard limestone	Soft limestone
Mountainous.....	Vertical zonation	Vertical zonation	Vertical zonation
Ionean.....	Mediterranean forest, dominant laterization	Terra rosa	Rendzina
Aegean .....	Dry Mediterranean forest, low laterization	Terra rosa	Rendzina
Northern.....	Gray forest and chestnut, low laterization	Terra rosa	Rendzina

Table 3 summarizes the foregoing remarks concerning the classification of Greek soils. This tentative classification cannot be considered as definite. Some divergence from the theoretical basis of the classification is already known, especially with regard to the formation of terra rosa.

From the description of the principal soil-formation processes, the reader may have in mind the principal features of the soils of Greece. But other aspects of the two main interzonal soils, the terra rosa and the rendzina, warrant further discussion.

Terra rosa soils comprise the most widespread single group in Greece. In spite of the powerful influence that limestone exerts on their formation, red soils that must be classified as Mediterranean terra rosa are formed also on other parent materials. This supports the opinion that the old definition of terra rosa as soil that has been formed through the influence of the Mediterranean climate upon limestone exclusively is obsolete, and that, under certain conditions, the Mediterranean climate, working upon other materials, also can form terra rosa. In Greece, parent materials that lack even traces of limestone are completely de-

veloped into terra rosa. To explain this phenomenon, a closer examination of some features of terra rosa is necessary.

Of all the features of terra rosa, that of the concentration of iron has been studied most intensively. The reason perhaps is that iron provides the most apparent macroscopic characteristic, the red color. In any event, a high concentration of iron is considered to be a dominant feature in the formation of red soils. But what is the influence of calcareous parent material upon this concentration? While still rock, partly weathered limestone favors the penetration of iron into its upper layers. No matter how compact a limestone may be, its structure might well be considered, from a wider point of view, as that of a sponge. Its cracks give to the rock, as a whole, a structure completely different from the mineralogical features of the mineral. The peculiar phenomena of circulation of water in limestone, known as *karst phenomena*, have their foundation in the fact that this compact mineral presents innumerable openings and passages for water. Through these, the underlying iron solutions can move upward, especially in climates with low precipitation and high evaporation. The result is that, from the early stages of weathering of limestone, iron may be fixed in its mass, more intensively during a long dry period. A flying trip to those areas of Greece that are covered by limestone rock is enough to persuade one that early upward movement, penetration, and fixation of iron are widespread. In parent materials that are poor in calcium, iron is fixed exclusively through the reaction of the OH ion upon the positively charged oxide of iron, with resulting coagulation. Where calcium is abundant, the iron is precipitated through its direct contact with limestone. Under the Mediterranean climate, upward movement and fixation of iron and aluminum are always prominent processes. Surface concentration of iron and red color of soils are possible, too, in other than limestone parent materials. The existence of limestone, therefore, is not a prerequisite of this process, but simply accelerates it.

In another, purely optical way, limestone helps the formation of the bright red color of terra rosa. The white limestone, in combination with the red of iron oxide, gives the characteristic brightness of terra rosa. But other minerals, too, can give similar colors. It is obvious that the investigation of terra rosa cannot be restricted to clarification of the role of iron and observations on color. Further investigation might show that the principal reactions occurring in its formations are helped by the existence of limestone but are not determined by it.

At any rate, further investigation of terra rosa depends upon elucidation of the influence of both the Mediterranean climate and the different forms of calcium on the decomposition of the nuclei of the aluminous-iron-silicates and on the movement and fixation of all the important soil constituents. Obviously, the Mediterranean terra rosa has not yet been investigated thoroughly enough to provide a clear understanding of its formation and internal relationships. In the early part of the century, mineralogists were so struck by the diversity of conditions and properties of terra rosa that they used to say, "Terra rosa is terra incognito." The hopeless position of the early mineralogists came from the fact that they tried to solve their problems on the basis of the *status quo*,

that is, they looked upon the geological and soil phenomena as immutable and lacking mutuality. Modern soil science is better able to solve similar problems because of its ability to consider soil phenomena as part of a dynamic process.

Some remarks are perhaps necessary about the other important group of interzonal Greek soils, the rendzina, or humus-carbonate soils, especially in relation to the role of calcium in the fixation of humus. We have already seen that, under the influence of soft limestone, vast areas of soils in Greece, both on mountains and on plains, are tending to become rendzinas. The most prominent feature of these soils is their high content of both calcium and humus. The interrelation of calcium and humus in rendzina soils involves the controversial issue of the influence of calcium on the fixation of organic matter. It is generally considered that the calcium of rendzina soils is primarily responsible for this accumulation. Is this action common to all climatic conditions and forms of calcium?

Admittedly, one of the principal causes of the fixation of organic matter in chernozem soils is the action of calcium. Through colloidal reactions, calcium accelerates the coagulation and stabilization of organic matter. There is no more elementary farming concept, however, than this, that calcium aids in the decomposition of organic matter. That organic matter added to noncalcareous soils is preserved better than in calcareous soils, is one of the ABC's of the farming of these areas. How can we explain these contradictory phenomena?

The processes involved in the mutual influence of organic matter and calcium in the soils can be classified into three groups: colloidal processes, dominated by the coagulating action of calcium on organic colloids; processes arising from chemical reactions; and biological processes. Generally speaking, an active form of calcium greatly accelerates decomposition of organic matter. In the final period of decomposition of organic matter, calcium, in an active form, combines readily with the negative ions, freeing the cation  $(\text{NH}_4)^+$ . On the other hand, reaction of the Ca ion with humus hampers decomposition of organic matter. These chemical and colloidal reactions of calcium with humus are not completely independent but are, within limits, influenced by the environment. Biological reactions are also much more strictly shaped by the environment. In the study of the formation of rendzina, it is necessary, therefore, first to clarify the action of the different compounds of calcium on the organic matter under the specific conditions of the environment, and second, to throw light on the contradictory behavior of calcium on the soil constituents that diverts soil formation in a direction other than the one determined by the climate. This action of calcium upon organic matter is the central point for the study of rendzina soils of Greece.

Despite the fact that calcium acts as a strong independent factor in the formation of the soils, climatic conditions play a significant role. In Greece, the prolonged dry hot summers, which destroy the colloids, not only fail to help in the colloidal reaction of calcium that leads to the fixation of organic matter, but also hamper vigorous activity of microorganisms. In consequence, the chemical action of calcium, which is speeded up during the hot summers, be-

comes of paramount importance. The resultant of these actions provides the clue to the effect calcium has on the decomposition or fixation of organic matter. It may be assumed that the presence of calcium, at least in its active forms, leads, during the summer, to rapid decomposition of the organic matter by chemical processes. The temperate winter helps the action of microorganisms and, as the presence of calcium facilitates the biological processes, the rate of decomposition is speeded up. On the other hand, the winter biological action aids in the formation of new organic matter. But perhaps the most important action during the winter that counteracts the destructive action of chemical processes of summer is the colloidal action of calcium, which probably helps greatly in the fixation of organic matter. These very important processes are, of course, still very far from clarification.

In any event, under the concrete conditions of Greek parent material and climate, no field offers greater reward for the soil scientist than a study of the powerful influence of calcium on the formation of soils, especially its influence on the fixation of organic matter, on the decomposition, coagulation, and leaching of the soil constituents, and on the development of plant life. Although the great variety of Greek parent materials and climate present tremendous difficulties for a comprehensive classification of the soils, they provide an excellent field for study of the influence of perhaps the most active constituent of Greek parent materials, the calcium, upon the different processes of soil formation.

Although the Mediterranean red soils, the rendzinas, the Mediterranean forest soils, and the gray-brown forest soils cover most of the land, an evolution toward solonetz and solonchak is not unknown. To a certain extent, this evolution occurs simultaneously with and overlaps the other soil processes. It is certain that salinization is gradually forming a new type of soil, but, in its early stages, this process of concentration of salts on the surface is going on parallel to and independently of the other soil processes. As a consequence of the importance of the upward movement of the salt, these parallel evolutions are common. Under these conditions it is only natural that confusion arises in the characterization of solonetz and solonchak soils.

With the execution in recent prewar years of large projects for drainage and protection against floods, new and grave problems have arisen in Greece in relation to the concentration of salts. Through these projects, about a quarter million acres have been brought under cultivation and double this area has been protected from floods. The problems connected with peat soils that have arisen in the drained area will not be dealt with here. Suffice to say that, in general, the handling of peat soils is easier in Greece than in northern climates, since the decomposition of organic matter is usually faster. But the significance of the movement of salts in the areas protected from the floods is closely related to our subject. Despite the absence of comparative analyses showing the salt content of the soils before and after execution of the projects, it is obvious that not only is the salt content of these soils rising but a real salinization is taking place. The floods unquestionably took lives, destroyed villages, ruined crops, eroded and filled some fields with stones, to the point of rendering them unfit-

for cultivation, but at the same time, they improved the soils of the flooded areas. Most of the soils in the inundated plains were improved in texture and structure and were fertilized for a period of years, until a new flood occurred. Unlimited quantities of water, forcibly percolated through the soils, washed out the salts and hampered the salinization process. Since the principal measures against the floods were the deepening of the beds of rivers and the construction of dikes along the banks, all these very important functions of floods were suspended. The projects brought a substantial surface increase in salts. Furthermore, the absence of floods lowered, in many cases, the level of the ground water. In some areas the water, at its new level, is unable to rise to the surface during the dry springs and summers of Greece. Apart from its significance to the well-being of crops, this lower moisture of the soils that were protected from the floods makes a given quantity of salts more harmful to the plants. Furthermore, the increased quantity of salts, as a consequence of the inadequate washing, causes a quicker drying and hardening of the upper layers.

The experience of Greece with engineering works for flood control may throw new light on the assumption that the traditional constructions may cause, at least in semiarid and arid countries, serious and dangerous disturbances to the existing equilibrium of organic matter, fertility, moisture, and salts. This, of course, is not a reason for condemning execution of flood-control projects, but it is a reason for advocating improvement in the prevailing technic.

It was hoped that irrigation would put things straight. Nevertheless, the usual method of irrigation cannot replace the natural effects of floods, which, as we have seen, were both a calamity and a blessing. Irrigation regulates water far more effectively to the physiological requirements of plants. But irrigation, at least as it is now applied, does not afford to soils the large amounts of clay, humus, and nutrients deposited by floods. Neither does it hamper the process of salinization to the same degree as did the floods.

The aforementioned projects for flood control were completed a score of years ago, but it is still too soon to do more than speculate as to where the soils are heading. Nevertheless, it may be safely concluded that new measures for flood control and for irrigation should be developed, at least in arid subtropical countries. The basis of these new practices should be strict application of the obvious rule for arid regions that no more water, fertility elements, silt, and clay should go into the sea after execution of the projects than before. This principle implies that the needed construction will not aim at absolute prevention of floods but rather at their regularization so that the water will be distributed as smoothly as possible on the plains. Irrigation projects designed for both winter and summer should be combined with operations against floods so that the washing of the salts and the addition of fertility elements and mud would continue as heavily as possible. Reforestation, control of erosion, and building of mountain dams forming reservoirs for water in the upland will prevent large floods, will keep in place stony material formerly brought down by floods, and will form, in time, new precious lands in the up-country. No flood-control project that consists merely in raising banks of rivers, digging ditches, and

deepening river beds is advisable for Greece. Experience gained from projects already realized in Greece and in a number of other arid subtropical countries has thrown ample light on the subject and can help in the formulation of invaluable rules. Greece is too poor in its soil, too narrow in its geographical formation, and too dry to permit the extravagance of sending to the sea through special projects more water and mud than are going there through natural processes. On the contrary, no means should be spared to keep every additional drop of water, molecule of mud, and gram of the fertility elements in the soil of the country. This is the principal task of our generation.

As erosion is an almost universal phenomenon in Greece, it modifies extensively, and sometimes deeply, the soil groups described in this paper. The final effect of erosion is the formation of skeleton soils but, before this happens, other interesting developments come into play. For instance, humocarbonate soils develop very often through erosion of red soils. This means that the fundamental soil-formation processes dominating in Greece, as a consequence of its climate, are going on beneath such characteristic interzonal groups as the humo-carbonate soils. The results of these fundamental processes are not completely wiped out by the powerful influence of soft limestone on the formation of rendzina. On the other hand, it is interesting that alluvial deposits sometimes differ completely from the soils from which they were eroded. During their transportation, the soil compounds are differentiated according to their specific gravity and size and, consequently, are moved to different distances. The result is that the chemical composition, texture, and structure of the new alluvial soils are by no means similar to those of the old soils. This is particularly marked in the erosion of the red soils. Among the mineral constituents, the iron and aluminum compounds are generally transported much farther, not only because of their specific gravity but because of their ability to form colloidal and silty fractions. It is undoubtedly a very peculiar phenomenon that red soils are not always formed from sedimentation of the materials coming from red soils.

#### SUMMARY

This study shows how the climate, parent material, vegetation, and topography of Greece determine the processes by which the main soil groups of the country are formed. Special emphasis is placed on the influence of the calcareous parent material, which is very widespread in the country, on soil formation. A classification of Greek soils is given. The relation of Greek soils to lateritic soils, the role of limestone in the formation of terra rosa and that of calcium in the fixation of organic matter in rendzina soils, and the concentration of salts at the surface, especially in the light of flood-control projects, are principal topics of the study.



# MOLYBDENUM DEFICIENCY OF THE CITRUS PLANT<sup>1</sup>

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More and more evidence is accumulating that the element molybdenum is essential to plant life. The role played by this element in the growth of micro-organisms has been well reviewed and investigated by Mulder (7).

According to Mulder (7), the presence of small amounts of Mo seems to be a requirement for the utilization of nitrate nitrogen by *Aspergillus niger*, but when ammonium salts are the source of nitrogen, much less Mo seems to be required. This indicates that the Mo functions perhaps catalytically in the reduction of nitrate nitrogen to ammonia. Mulder has also shown that Mo may be necessary for the proper functioning of denitrifying organisms, and that the nitrogen-fixing ability of some organisms seems to be quite definitely dependent on the presence of Mo.

Work on the essentiality of Mo for higher plants is not so extensive. Arnon (1) obtained improved growth of barley plants in the presence of Cr, Mo, and Ni, with ammonium salts as the sole source of nitrogen. He later (2) obtained the same kind of results with asparagus and lettuce, Mo being one of a whole host of added elements. In 1939, Arnon and Stout (3), using solution cultures, demonstrated that Mo seemed necessary for the proper development of the tomato plant. The deficiency symptoms were characteristic, consisting of a new type of mottling on the lower leaves and a necrosis and curling of the edges of these leaves. As little as 0.01 p.p.m. of Mo in the culture solution was sufficient to cause recovery, and spraying a Mo compound on the foliage corrected the deficiency.

Hoagland (5), working with Myrobalan plum seedlings in culture solutions, showed that a deficiency of Mo in these plants resulted in similar symptoms, namely, a diffuse mottling, with many leaves showing necrotic areas at the tips and margins. Piper (8) showed that Mo seemed to be necessary for proper development, especially of the seed portion, of oat plants grown in nutrient solutions, and that a concentration of 0.02 p.p.m. was more than enough.

In studies of lettuce grown in culture solutions, Brenchley and Warington (4), and later Warington (13), found that Mo had value in improving the health and growth of the plant. Warington was not always successful in producing the deficiency symptoms in the supposed absence of Mo. In view of the extremely low concentrations required by some nonlegumes, it is not unlikely that the variable success with lettuce was due to slight contamination. Mulder

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7), using tomato, barley, and oat plants in sand cultures, showed that these plants required Mo, especially when nitrates were the source of nitrogen; when the nitrogen was supplied as ammonium salts, the need for Mo was not nearly so great.

Since the growing body of evidence may well indicate the need for Mo by higher plants, it was deemed advisable to investigate the Mo requirement of the citrus plant for healthy growth, as well as the symptoms and control of any possible deficiency. This study was especially advisable in view of the fact that definite responses of certain field crops to Mo fertilization in the field have been reported from Australia.

#### EXPERIMENTAL PROCEDURE AND RESULTS

Rooted lemon cuttings were grown in a greenhouse for 15 months in highly purified culture solutions with and without additions of Mo at two low concentration levels. Well-defined deficiency symptoms were quickly eliminated by addition of very small amounts of Mo to the culture solutions, and also by spraying small amounts of a soluble Mo compound on only a small portion of the plant's foliage. By means of spectrographic analysis, a complete check was maintained continually on freedom from Mo contamination in all phases of the experiment.

##### *Physical setup of culture experiments*

The experimental work was carried out in equipment described earlier by Liebig, Vanselow, and Chapman (6). Rooted Eureka lemon cuttings were grown in culture solutions in 7.5-liter Pyrex glass battery jars, which were provided with bakelite covers having varnished wooden plugs in which were inserted split corks for supporting the plants. Sintered Pyrex glass aerators were used on all the cultures to keep the plants well supplied with oxygen. The glass jars were painted on the outside, first with black paint and then with a coat of aluminum paint, to exclude light and keep down the growth of algae. All the equipment used in this work received a thorough scrubbing with a brush and a soap solution, followed by treatment with warm, approximately normal sodium hydroxide solution, dilute hydrochloric acid, and finally with distilled water.

##### *Method of analyzing for molybdenum*

By the combination of a chemical concentration process and spectrographic analysis, it was possible to check the purity of all chemicals used in the experiments, and also any possible contamination. The lower limit of detectability of the colorimetric KCNS-SnCl<sub>2</sub>-ether method (9, p. 333) is about 1 to 2  $\mu$  of Mo. With the spectrographic equipment available, 0.05  $\mu$  of Mo could be positively identified and measured. But even this sensitivity was not enough to permit using the direct-arc technique for checking the purity of the chemicals used in the culture solutions. Any desired sensitivity can be attained, however, by making the KCNS-SnCl<sub>2</sub>-ether extraction on a suitably sized sample and deter-

mining the Mo spectrographically in the residue of the ether extract. The residue from this ether extract contains virtually all the Mo originally present in the initial sample, and its weight varies from about 4 to more than 50 mgm., the amount depending on the care used in the separation and the character of the substance being analyzed. For the salts that constituted the major components of the culture solutions, a 25-gm. sample was used.

This method was also used for determining the Mo content of the tissue samples. A suitably sized sample of the dried plant material was ashed at 450° to 500° C. in a silica evaporating dish, and the ash was dissolved in redistilled HCl solution. The KCNS-SnCl<sub>2</sub>-ether extraction was made on the dissolved ash, and the Mo determined spectrographically in the residue of the extraction.

#### *Preparation of the nutrient solution*

The composition of the basic nutrient solution, expressed in milligram-equivalents per liter, was: Ca, 6.28; Mg, 3.77; K, 2.57; Na, 0.1; Cl, 0.1; NO, 10.0; PO<sub>4</sub>, 0.33; and SO<sub>4</sub>, 2.50. Boron, Fe, Mn, and Zn were provided at the rate of 0.1 p.p.m. and Cu at 0.05 p.p.m.

All attempts to remove the last measurable traces of Mo from either the culture solution or the separate salts by the technique of Steinberg (10) or by the modification of Stout and Arnon (11) failed completely. It was therefore necessary to purify the separate salts by whatever procedure was most suitable. The extraction-spectrographic test for Mo was made on 25-gm. samples of all the salts used in the nutrient solution. Several of these salts, namely, KH<sub>2</sub>PO<sub>4</sub>, KNO<sub>3</sub>, and MgSO<sub>4</sub>, contained no detectable Mo. No Ca(NO<sub>3</sub>)<sub>2</sub> or Mg(NO<sub>3</sub>)<sub>2</sub> free of Mo could be located, hence both these nitrates had to be purified by the method described by Vanselow and Liebig (12):

Equal volumes of 2 *N* solutions of Ca(NO<sub>3</sub>)<sub>2</sub>, or CaCl<sub>2</sub>, and KOH were slowly mixed under constant agitation; the precipitated Ca(OH)<sub>2</sub> was rapidly filtered off and washed with cold redistilled water on Büchner funnels. After being dried, the Ca(OH)<sub>2</sub> was analyzed for Mo, and if none was detected, the Ca(OH)<sub>2</sub> was converted to the nitrate by solution in redistilled nitric acid.

This precipitation method yields variable results. In only approximately half the cases does it yield a product free of Mo; hence each batch of Ca(OH)<sub>2</sub> or Mg(OH)<sub>2</sub> had to be separately checked for the absence of Mo. No effort was made to ascertain the cause of the variable success of this purification procedure.

A spectrographic examination by direct arcing was also made of all the major components of the culture solution. This was done to be certain that undesirable elements were not present in excessive amounts.

All the water used in this study was redistilled from all-Pyrex-glass stills. The purity of this water was verified by evaporating 2 liters to a small volume and making the spectrographic determination on the residue of the ether extract. No Mo was detected; hence the amount present was less than 50 parts in a million million.

The minor elements were supplied by additions of CuSO<sub>4</sub>, FeSO<sub>4</sub>, H<sub>3</sub>BO<sub>3</sub>, MnCl<sub>2</sub>, and ZnSO<sub>4</sub>. Since only extremely small amounts of each of these ele-

ments were used, checking for Mo contamination by the direct arcing of the dried salts was considered to be sufficient.

The culture solution was made from redistilled water and the following three stock solutions, which were, in turn, made from 1 *M* solutions of the purified salts:

1.  $\text{Ca}(\text{NO}_3)_2$ , 1,180 ml.;  $\text{Mg}(\text{NO}_3)_2$ , 238.5 ml.;  $\text{KNO}_3$ , 922.5 ml.;  $\text{NaCl}$ , 37.5 ml.; and water to give a volume of 2,500 ml.
2.  $\text{MgSO}_4$ , 375 ml., diluted to 400 ml.
3.  $\text{KH}_2\text{PO}_4$ , at 0.83 *M*.

For each 7.5-liter jar, 50 ml. of stock solution No. 1, 10 ml. of No. 2, and 1 ml. of No. 3, were used with enough redistilled water to make 7.5 liters. The solution was adjusted to a pH of 4.5 with 0.1 *N* KOH or 0.1 *N*  $\text{HNO}_3$ , as the case required. This basic culture solution was analyzed for its Mo content; 2 liters was used for the test, and no Mo was detected. Thus this culture solution had less than 50 parts of Mo per million million. Its Mo content was probably considerably less than this as is indicated by data presented in this article. No further attempt was made to determine the actual value.

#### *Growing the test plants*

Cuttings of Eureka lemon were rooted in sand in a propagating bed. Plants as nearly uniform as possible were transferred to the solution cultures in the 7.5-liter Pyrex glass jars on January 30, 1947. Twenty-four such cultures were set up, with three rooted plants in each jar. The reaction of the culture solutions was adjusted daily to a pH of 4.5 by means of 0.1 *N* KOH or 0.1 *N*  $\text{HNO}_3$  solutions, the amount of acid or alkali required being ascertained from the pH and the previously determined titration curve of the culture solution. Water lost by transpiration was replenished daily. The culture solutions were made up fresh every 4 or 5 weeks. At the time of the first change, an aliquot was taken of the old culture solution from each of the 24 jars, and a 2-liter sample of the composite was analyzed for Mo. None was detected. Though this result does not exclude the possibility of slight contamination, it does indicate the absence of contamination beyond the capacity of the relatively small plants to assimilate Mo.

Four weeks after transfer of the plants to the solution cultures, the new cycle of growth had attained sufficient size that the old leaves on the plants could be removed. It was reasoned that by removing this old foliage, part of the Mo reserve in the plants would be eliminated, thereby hastening the onset of possible deficiency symptoms. These old leaves were analyzed for Mo, as were the leaves and stems of the plants sampled at the time of transfer to the solution cultures. The results are given in table 1. These data show that the Mo in the plant is easily transferable, and it may be inferred that the new growth is drawing upon the Mo originally present, and that the plant is not getting any appreciable amount from the culture solution.

Insect infestation was controlled by hand-picking, when infestation was





slight, and by a spray program. All spray materials were checked for Mo content before use.

Differential Mo additions were started 6 weeks after planting. Minor element and Mo additions were made only at the time of change of solutions. It was soon found, however, that as the plants grew, the amounts of Fe, Mn, and Zn had to be augmented; accordingly, these three elements were added twice weekly at 0.1 p.p.m. The Mo additions were made at two levels, three jars receiving additions of 0.001 p.p.m. and three more jars receiving 0.0001 p.p.m. In the latter three jars, the concentration was soon increased to 0.01 p.p.m., because it was felt that the original level would be too low to be of any benefit. As it turned out, it was regrettable that this lowest concentration was eliminated.

By May 1, 1947, 3 months after transfer to the solution cultures, the plants had become rather crowded; the number was therefore reduced to two plants per jar, only the most uniform plants being retained. At this time no visible difference was noted between the plants that did and did not receive Mo.

TABLE 1

*Molybdenum content of stems and leaves of original rooted lemon plants, and of leaves removed after growth in basic culture solution*

TISSUE ANALYZED	Mo CONTENT OF DRY TISSUE
	<i>p.p.m.</i>
Leaves of original plants*	0.36
Stems of original plants*	0.26
Leaves removed February 14, 1947	0.16
Leaves removed March 3, 1947	0.14

\* At time of transfer to solution cultures, January 30, 1947.

When there still was no noticeable difference in the plants after 5 months of growth, it was thought that the Mo, if required, might be linked with nitrogen utilization, and that deficiency symptoms might conceivably develop sooner if ammonium salts were used as the sole source of nitrogen. It was decided to place half of the cultures on an all-ammonium-nitrogen diet. Accordingly, the necessary salts were purified or prepared, and 12 of the 24 cultures were changed to this new nutrient solution about July 1, 1947.

These ammonium-nitrogen cultures had a great tendency to become too acid, frequently dropping to a pH of 3.0 in the space of a few hours. The roots soon developed an unhealthy condition: they became brown and had a tendency to rot; even the tops showed some signs of distress. In view of this difficulty, and inasmuch as the plants left on the nitrate-nitrogen basis were (3 weeks later) developing pronounced symptoms hitherto not seen on citrus, the attempt to keep these plants on an all-ammonium source of nitrogen was abandoned.

All but four of the jars were put back on the original nitrate culture solution; these four jars were changed to a nutrient solution in which half of the nitrogen was supplied as nitrate and half as ammonium. Most of the time these four cultures had a tendency to become acid, but not to so great an extent as with the

all-ammonium-nitrogen solution. Adjustment to a pH of 4.5 was done mostly with 0.1 N  $\text{NH}_4\text{OH}$ , although some KOH was used.

### *Development of deficiency symptoms*

Slightly more than 5 months of growth had taken place before any visible symptoms developed. At this time a few leaves of the mature last cycle of growth on some of the plants that were receiving no Mo were beginning to show slight interveinal chlorosis or mottling. During the next 4 weeks, the new cycle of growth on most of the controls in the all-nitrate-nitrogen cultures developed this mottled condition. The leaves of the new cycle attained full size, or nearly so, without developing any unusual appearance other than a rough texture, probably due to enlarged oil glands; but instead of maturing to dark green, healthy leaves, they rapidly become mottled.

The leaves of this mottled cycle may or may not develop necrotic spots in the mottled areas. Apparently, if the Mo deficiency is severe enough, these necrotic areas appear, enlarge, and extend to the margins, causing the leaf edges to curl. The necrotic leaves are usually shed, but few of the denuded twigs die. Occasionally, small excretions of gum appear at the internodes.

The plants which had been on the all-ammonium-nitrogen solution for 3 weeks and were back on the all-nitrate-nitrogen solution developed the characteristic deficiency symptoms about 3 to 4 weeks later. These deficiency symptoms were similar to those reported by Arnon and Stout (3) for tomatoes, and by Hoagland (5) for plums. Slight differences are to be expected from different genera. Figure 1 shows two leaves in the mottled stage and one typically necrotic leaf, flattened to display the patterns of the mottled and necrotic areas. Figure 2 shows a typical cycle of necrotic leaves, with a new cycle of growth coming on. These necrotic leaves would have dropped off soon.

Early in August, 1947, after 7 months in the solution cultures, three leaf samples were taken for analysis: (a) young leaves from the plants receiving 0.01 p.p.m. Mo, (b) young leaves from the 0.001-p.p.m. cultures, and (c) young necrotic leaves from the deficient plants. The Mo contents of these samples were: (a) 1.1 p.p.m., (b) 0.25 p.p.m., and (c) less than 0.02 p.p.m. In the necrotic leaf sample no Mo was detected, because the small sample size precluded the possibility of detecting less than 0.02 p.p.m. of Mo. These few values are completely consistent with the concentrations of Mo supplied in the culture solutions and with the symptoms.

The subsequent new cycle of growth differs somewhat from the normal in that the new shoots are more numerous and occur at more of the leaf axils. If no Mo is supplied to the plant, the mottled and burned condition and the abscission of the leaves develop more rapidly in succeeding cycles of growth.

### *Correction of deficiency*

In August, two cultures containing the most severely affected plants were given additions of 0.1 and 0.5 p.p.m., respectively, of Mo. The relatively high dosage of 0.5 p.p.m. Mo was reduced to 0.1 p.p.m. at the next change of culture solution. The next and all subsequent cycles of growth developed normally



on these two treated cultures. Thus the deficient condition is quickly rectified by addition of small amounts of Mo to the culture solution. This is in complete agreement with the experience of Arnon and Stout (3) with tomato plants. Only in leaves having just a slight degree of mottling does addition of Mo cause gradual disappearance of the mottling. The severely affected leaves are not improved in appearance, but abscission of the necrotic leaves is greatly delayed.

By the middle of October, 1947, the status of the plants was as follows: None of the plants receiving Mo additions showed deficiency symptoms of any degree or kind. All the plants in the Mo-deficient nitrate nutrient solutions showed symptoms of greater or lesser degree; only three of the 24 plants in this category



FIG. 1. LEMON LEAVES SHOWING (LEFT AND CENTER) MOTTLED STAGE AND (RIGHT) NECROTIC STAGE OF MOLYBDENUM DEFICIENCY

These leaves were flattened before being photographed

had no necrotic leaves, but they did have several mottled cycles (sample 2, table 2). The plants in the two nitrate-ammonium nutrient cultures which received no Mo had only the faintest visible degree of mottling (sample 3, table 2). This rather slight manifestation of deficiency symptoms may have been due to slight contamination from the relatively large amounts of 0.1 *N* KOH solution used for adjustment of the pH of the culture solution. As will be shown later, this possibility of contamination is supported by the analytical data. Four months later, the plants had developed very pronounced mottling but still no necrosis.

By October, 1947, the plants had attained sufficient size to cause undue crowd-

ing. This condition was corrected by harvesting half of the plants, leaving only one plant in each jar. The choice of plants to be harvested was governed by the following considerations: A few of the controls had developed only relatively mild deficiency symptoms. These were harvested so that all the control plants remaining had well-developed deficiency symptoms, since it was planned to investigate other corrective procedures.

The harvested plants were classified according to the degree of severity of the symptoms. The young leaves and the fine roots were analyzed for their



FIG. 2. NECROTIC STAGE OF MOLYBDENUM-DEFICIENT LEMON TREE  
Note typical curling of leaf edges

Mo content by the extraction-spectrographic method. They were also spectrographed by direct arcing of the ash to determine the status of the other minor elements. The resulting data are presented in table 2. From these data it becomes evident why the plants required 5 months of growth before deficiency symptoms developed: the leaves and stem of the rooted cutting originally contained enough Mo for a fifteenfold to twentyfold increase in size of the plant before a deficiency level was reached, assuming that no Mo was present in the nutrient solution.





The Mo content of the leaves is entirely consistent with the Mo dosage of the culture solutions and the severity of the deficiency symptoms. The leaves of the plants in sample 3 had twice the Mo content of those in the other two zero-Mo cultures, and this undoubtedly accounts for the slight deficiency symptoms. This higher Mo content could be explained in either or both of two ways: First, the plants of sample 3 were grown in the nitrate-ammonium nutrient solution, and the relatively large daily additions of KOH or  $\text{NH}_4\text{OH}$  solutions required for maintaining the pH at the proper level very likely contributed small amounts of Mo. Second, the roots of these plants were always in a poor condition, and as the result of much rotting and shedding of the fine roots the size of the root system was only a fraction of that of the other plants. As the rotted roots were shed, the Mo contained in them became available to the plant.

TABLE 2

*Effect of molybdenum content of culture solution on deficiency symptoms of leaves and Mo content of young leaves and fine roots of lemon plants*

SAMPLE NUMBER	Mo IN CULTURE SOLUTION	DEFICIENCY SYMPTOMS OF LEAVES		Mo CONTENT*			
				Leaves		Fine roots	
		Mottle	Necrosis	E-S	D-A	E-S	D-A
	p.p.m.			p.p.m.	p.p.m.	p.p.m.	p.p.m.
1	None	Severe	Severe	0.011	—†	0.068	—
2	None	Moderate	None	0.013	—	0.072	—
3	None	Doubtful	None	0.024	—	0.058	—
4	0.001	None	None	0.27	—	...	4.5
5	0.01	None	None	1.1	1.0	...	18
6	0.1	None	None	3.0	2.8	...	60

\* E-S = Extraction-spectrographic method of determination; D-A = direct arcing of ash.

† Dash indicates no Mo detected. (Lowest Mo content detectable by direct arcing of the tissue ash is 0.3 to 0.5 p.p.m.)

This resulted in a higher Mo content of the leaves and a delay in the development of the deficiency.

Spectrographic examination by direct arcing of the ash of the young leaves revealed nothing out of the ordinary as regards the other minor elements, either essential or nonessential, with the exception of Ba and Sr. The purification process used for eliminating the Mo from the Ca and Mg salts also practically eliminated the Ba and Sr usually present even in the c.p. calcium salts. This resulted in very low Ba and Sr contents of the plants, but no ill effects of any kind were ever noted on those plants which received Mo. However, in order to check any possible effect that this low Ba and Sr level may have had on those plants deficient in Mo, a few plants severely deficient in Mo were given Ba and Sr singly and in combination, at 1.0 p.p.m. In no case was any beneficial effect noticed after 4 months of Ba and Sr additions.

Nine months after transfer of the plants to the culture solutions, other additions of Mo at lower concentrations were made to cultures containing deficient plants. Two jars were given additions of 0.001 p.p.m. of Mo. The plants in these jars showed only a small degree of mottling in the next cycle of growth, and all subsequent growth was normal. To the nutrient solution of two other very deficient plants was added 0.0001 p.p.m. of Mo. These plants continued to produce somewhat mottled leaves for two more cycles of growth, but there was no necrosis, and all subsequent growth was normal.

In December, 1947, two severely deficient plants, each of which had two approximately equal-sized branches, were selected for Mo spray treatment. Four milligrams of Mo as  $\text{KMoO}_4$  solution was sprayed on the older leaves of one branch only, the rest of the plant being protected during the spraying. Two months later all new growth on all parts of these two plants had matured normally. Thus it is apparent that only a portion of the deficient plant need be sprayed with a soluble Mo compound to ensure recovery of the entire plant. These results are in agreement with those of Arnon and Stout (3) on tomatoes.

In considering the remote possibility that some other element might be substituted for the required Mo, only those elements adjacent to Mo in the periodic table were investigated. This limitation to adjacent elements is quite logical, since one could hardly expect a greatly dissimilar element to be capable of simulating the function of an essential element. Two of the most severely affected cultures were given additions of the elements Co, Cr, Ni, Re, V, and W to the nutrient solutions, at a concentration of 0.001 p.p.m. each. (The elements Cb and Ta were not included because of uncertainty regarding the absence of Mo in the compounds available.) These six elements were added each time the nutrient solutions were changed, but even after 7 months no evidence of recovery was manifested. Figure 3 shows one of the severely deficient plants that received additions of these six elements to the culture solutions; the necrotic, curled leaves are very much in evidence. Figure 4 shows a perfectly healthy, normal plant—one that received 0.01 p.p.m. Mo at every change of solution. Both plants were photographed at an age of 14 months.

#### *Molybdenum in relation to ammonium versus nitrate nitrogen*

The necessary limitations to the magnitude of this experimental study precluded the possibility of a thorough investigation of the Mo requirement of the citrus plant when the nitrogen is available as an ammonium compound.

Admittedly, the plants of the two cultures supplied with ammonium nitrogen took much longer to develop the characteristic deficiency symptoms, but the leaves of these plants contained more Mo than did those of the nitrate-nitrogen cultures. This additional Mo no doubt came from the very much larger amounts of 0.1 N KOH solution used for maintaining the proper pH in the culture solution. The point is that these two plants finally did develop very pronounced mottling similar to that of the nitrate cultures, and two other plants grown in the same ammonium nitrogen and nitrate nitrogen nutrient solution, but receiv-



FIG. 4. NORMAL, HEALTHY, 14-MONTH-OLD LEMON TREE  
SUPPLIED ONCE A MONTH WITH 0.01 P.P.M. MO  
IN THE NUTRIENT SOLUTION



FIG. 3. MOLYBDENUM-DEFICIENT, 14-MONTH-OLD LEMON  
TREE IN SOLUTION CULTURE; LOWER PART OF PLANT IS  
NORMAL; UPPER PART IS TYPICALLY MO-DEFICIENT

ing Mo additions, failed to show any mottling. Results of these few cultures would indicate that Mo is required for proper development of the citrus plant, regardless of the kind of nitrogen supplied.

#### SUMMARY

Rooted lemon cuttings were grown for 15 months in solution cultures highly purified with respect to the element molybdenum. Plants in all cultures deprived of this element developed characteristic symptoms of mottling and necrosis of the leaves when the original Mo in the cuttings had been attenuated by transfer to, and utilization by, the new growth. No cultures receiving Mo developed symptoms of any kind.

The Mo content of the dry matter of young leaves of the deficient plants was 0.01 p.p.m.; that of the leaves of plants in cultures supplied with 0.001 p.p.m. Mo was 0.2 to 0.3 p.p.m. Plants just beginning to exhibit a mottled condition had 0.024 p.p.m. of Mo in the dry matter of the leaves.

Mo-deficiency symptoms of the plants were quickly eliminated by addition of 0.01 p.p.m. of Mo to the culture solutions. Even with additions as low as 0.0001 p.p.m., the plants recovered in a few months.

The deficiency was also easily and quickly overcome by spraying small amounts of a soluble Mo compound on the foliage; spraying of only a small portion of the foliage resulted in recovery of the entire plant.

None of the elements Co, Cr, Ni, Re, V, or W when supplied at concentrations of 0.001 p.p.m. in the nutrient solution, was found to be capable of reducing the severity of the deficiency symptoms.

The deficiency symptoms developed even when the plants were well supplied with nitrogen in the form of ammonium salts.

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# MIGRATIONS OF PHOSPHORUS AND OTHER ELEMENTS FROM VARIOUSLY PHOSPHATED SOILS, WITH AND WITHOUT CALCIUM FLUORIDE AND LIMING MATERIALS

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In the manufacture of phosphatic fertilizers the principle objective is to effect conversion of mineral calcium phosphates into forms that are rated and guaranteed as readily dissolvable, or "available," when delivered to the user. The manufacturer's guarantee is fulfilled when his product comprises the compositions claimed and verified by means of the "official" analytical methods. Then come the economic considerations of adaptability to particular soils, of liming supplements, and of the extent of the recovery of the incorporated phosphorus through phosphate-induced increase in crop growth and composition. The farmer may use a phosphate of 95 per cent "availability," and yet the response by the first crop seldom brings a recovery beyond 25 to 30 per cent of the incorporated phosphorus, and often small subsequent recovery from the larger fraction that undergoes fixation in the soil complex.

The soil chemist therefore faces the problem of ways and means for a better utilization of phosphatic fertilizers. He might chart an ameliorative treatment of the soil to diminish its capacity to effect phosphate fixation, and thereby induce an increase in the yields of phosphorus-enriched crops. Or he might develop types of phosphates that would be less likely to undergo ready leaching or excessive fixation while remaining in forms that the plant can utilize.

The early teachings were that incorporation of superphosphate into a limed soil would result in rapid formation of the tertiary calcium phosphate. Previous contributions from the Tennessee Station have demonstrated that this assumption is not warranted (8, 9, 10). Although monocalcium phosphate does undergo rapid transition to dicalcium phosphate in its mixtures with limestone and with dolomite (8, 9), especially when those carbonate minerals are wetted (12), the successive transition to tertiary state is slow and does not proceed to completion, even in protracted aqueous suspensions with large excess of the carbonate materials (10). Yet, when a fraction of the potential development of the tertiary phosphate is generated in bulky dry and wetted mixtures, through reaction of superphosphate with limestone (12), with slag (14), or with powdery defluorinated rock phosphate (17) or in ammoniated superphosphate (16), the generated tertiary phosphate may react readily with component fluorides and pass into the apatite combination. Although such reversion and the attendant decrease in phosphorus availability take place in mixtures of superphosphate and liming materials made prior to the incorporations of those mixtures, it has not been shown that the apatite transition occurs to detrimental extent when superphosphate is incorporated in the limed soils. That possibility has been under

study at the Tennessee Station and has been explored at the Rothamsted Station (24).

Three contributions (18, 19, 20) from the Tennessee Station and the findings reported by Beater (1) demonstrated that the utilization of phosphorus was greater when the soils were limestoned at rational rates prior to the incorporation of monocalcium phosphate, so as to develop and prolong an adequate supply of dicalcium phosphate within the soil.

#### MIGRATION OF PHOSPHORUS AND ASSOCIATED INPUTS

It seemed logical to assume that the mobility of phosphorus as an ionized solute would serve as a reliable index to the "availability" and plant usage of that element from inputs of liquid and solid phosphates in soils of various character *per se*, and after changes resultant from incorporations of calcic, dolomitic, and fluoric materials. In the present paper the term *migration* is used to connote the passage of phosphorus and associated elements into the rainwater leachings from incorporations of various phosphatic materials, with and without supplements of  $\text{CaF}_2$  and liming materials. This contribution embodies the findings from three long-time lysimeter experiments concerning the factors that influence the duration of the state in which incorporated phosphates function effectively as sources of nutrient phosphorus for plants.<sup>1</sup>

One experiment was of 10 years' duration and dealt with the influence of repetitive incorporations of  $\text{CaF}_2$  upon the fate of phosphorus carried by a 2-ton-per-acre full-depth incorporation of rock phosphate and by equivalent inputs of three types of calcium phosphate in prelimestoned and predolomited soils.

A second experiment, of 12 years' duration, comprised a study of the migrations of phosphorus from upper-stratum incorporations of monocalcium and monomagnesium phosphates and of rock phosphate in unlimed soils and from corresponding incorporations of monocalcium phosphate in previously limestoned and previously dolomited soils versus the analogous migrations from like incorporations of the premixtures of the monocalcium phosphate with limestone and with dolomite.

In a third experiment the analyses of the rainwater leachings served to register (a) the distinctive migrations of phosphorus from inputs of  $\text{H}_2\text{PO}_4$ , of mono-, di-, and tricalcium phosphates, and of fused tricalcium phosphate in an acidic soil, and (b) the migrations induced through inputs of  $\text{H}_2\text{PO}_4$  and of monammonium and diammonium phosphates in a near-neutral soil.

The concomitant migrations of the associated elements and radicals were determined in each experiment. Although they were different as to their chief objectives, the three experiments were similar in that they sought to elucidate the transitions suffered by the phosphate inputs and the duration of their availability through determinations of the passage of phosphorus and associated elements into the rainwater leachings from 100-pounds of soil, m.f. basis, in lysimeters of 1/20,000 acre. The soils were maintained fallow throughout the experiment, so

<sup>1</sup> Weather precluded incorporations one year.

as to obviate the involvements incident to variance in growth of crops. Since the rainwaters that fell within the periphery of the above-ground part of the tanks suffered no surface runoff, the volumes of the leachings represent fractions somewhat larger than those would obtain for such rainwaters under field conditions. Nevertheless, a clarification of the fundamental relationships under study is afforded through the findings as to differential passages of the added elements into the rainwater drainage.

### Experiment I

Clarksville silt loam, of pH 5 (table 1), was used in this 10-year experiment, which was conducted under project title, "Divergent Effects of Limestone and Dolomite and Fluorine Compounds, as Affecting Fate and Availability of Soil Phosphates." The possibility that incorporations of the two types of limestone induce difference in the behavior of added fluorine had been suggested by an-

TABLE 1  
*Base exchange and pH values of soils used in the three phosphate experiments*

SOIL TYPE	NO.	EXCHANGE CAPACITY	EXCHANGEABLE BASES			EXCHANGEABLE HYDROGEN	pH
			Ca	Mg	Ca + Mg		
		m.e.	m.e.	m.e.	m.e.	m.e.	
Cumberland silt loam.....	6355	8.9	3.6	0.9	4.5	4.4	5.6
Cumberland subsoil.....	6356	13.0	3.6	1.5	5.1	7.9	5.0
Sequoia silt loam.....	6357	11.6	4.7	1.7	6.4	5.2	5.9
Calhoun silt loam.....	6358	6.2	5.5	0.9	6.4	0*	6.7
Clarksville silt loam.....	6671	7.3	2.5	0.8	3.3	4.0	5.5
Hartsells fine sandy loam.....	6725	5.2	1.4	0.3	1.7	3.5	4.5
Dewey silt loam.....	6726	9.6	11.2	1.2	12.4†	0	6.5

\* Contains 0.038 per cent of  $\text{CaCO}_3$ .

† Contains 0.041 per cent of  $\text{CaCO}_3$ .

alyses of the soils that had received such incorporations along with additions of barium silicofluoride (11). Those findings indicated that the enhancement in the outgo of magnesium from the dolomite served to accelerate and increase the outgo of fluorine. The analyses of the residual soils were made, however, prior to the demonstrated fixation of additive fluorine and its resistance to distillation in calcined soil charges of high content of magnesia (15), and before the use of the present proved procedure for the determination of fluorine content of soils (22, 27), and hence there exists an uncertainty as to the accuracy of the earlier analyses of the soils that received heavy incorporations of the barium silicofluoride and dolomite.

One experimental objective was to learn whether repetitive inputs of  $\text{CaF}_2$  would affect alike the availability of phosphorus carried by incorporations of the several calcium phosphates in limestoned and in dolomited soils through the ultimate transition indicated by the equation,  $3\text{Ca}_3(\text{PO}_4)_2 + \text{CaF}_2 \rightarrow \text{Ca}_{10}\text{P}_6\text{O}_{24} \cdot \text{F}_2$

(14). The intent was to enrich prelimestoned and predolomited soils through incorporations of several phosphorus carriers and then incorporate substantial inputs of  $\text{CaF}_2$  annually, so that the ultimate soils would be at hand for chemical and pot culture studies.

The 2-ton  $\text{CaCO}_3$ -equivalent incorporations of limestone and dolomite were made as stipulated in table 2, and all of the units then were allowed to "age" 2 months. The prescribed single inputs of tricalcium and dicalcium phosphates, of calcium metaphosphate, and of rock phosphate then were incorporated in full depth and were in equivalence to the input of rock phosphate, which was at the rate of 2 tons per 2,000,000 pounds of soil. In a supplemental series, like charges of limestone and of dolomite were mixed with calcium metaphosphate outside the soil, and the resultant mixtures were aged 24 hours before incorporation.

The collections of the leachings from the full-depth incorporations were analyzed periodically for fluorine and nitrogen content, whereas the quantities of phosphorus, calcium, magnesium, and potassium carried by the leachings were determined annually through analyses of the composites of the periodic collections. The passages of phosphorus into the leachings annually through the 12 years were invariably meager, and without significance, and therefore are not shown in table 2.

The annual migrations of calcium from the unsupplemented inputs of rock phosphate, tricalcium phosphate, and calcium metaphosphate were nearly equal. The  $\text{CaF}_2$  supplements to the tertiary phosphate and the metaphosphate induced additional migrations of calcium. Selective fixation of the fluorine of the repetitive incorporations of  $\text{CaF}_2$  is indicated by the fact that the calcium migrations from those incorporations exceeded greatly the quantities necessary to account for corresponding passages of calcium fluoride as such. Maximal release of calcium from the unsupplemented phosphate was from the dicalcium phosphate, and the input of  $\text{CaF}_2$  induced no further increase in the leaching of calcium from its combination with that phosphate. Every limestone incorporation caused an increase in the leachings of calcium, but the magnesium carbonate induced diminution in the outgo of calcium from the input of rock phosphate.

In general, the incorporated limestone was repressive to the outgo of magnesium. In the 19 instances in table 2, the inputs of calcium, or of calcium-magnesium, were also repressive to the outgo of potassium. The quantities of nitrate nitrogen carried by the leachings were relatively small and are not deemed as having registered distinct effects.

Annual outgo of fluorine from the rock phosphate was meager, whether the raw rock was incorporated alone or in association with limestone, dolomite, or magnesium carbonate. In every instance, however, the inputs of  $\text{CaF}_2$  caused an increase in the outgo of fluorine, the largest passages being those from the tricalcium phosphate units. Passage of fluorine from the  $\text{CaF}_2$  of the dicalcium phosphate units was similar to such passage from the corresponding metaphosphate, which may be considered a dehydrated monocalcium phosphate of fertilizer grade.

The cumulative 4,832-pound input of  $\text{CaF}_2$  into the soil systems of Experi-

ment I was far beyond the capacity of any phosphate incorporation to effect fixation of the fluorine of that input through the formation of calcium fluor-

TABLE 2

*Respective means of 10 annual migrations\* attributable to full-depth, single, simultaneous incorporations of calcic, magnesian, and dolomitic materials† and annual incorporations of CaF<sub>2</sub> in variously phosphated Clarksville silt loam*

INCORPORATED MATERIALS	CALCIUM AS CaCO <sub>3</sub> - EQUIVA- LENCE	MAGNESIUM AS CaCO <sub>3</sub> - EQUIVA- LENCE	POTASSIUM AS K <sub>2</sub> O	NITRATE N	FLUORINE‡ AS F
	lb.	lb.	lb.	lb.	lb.
338 Rock phosphate alone.....	39	-5	-1.2	0.7	0.23
339 Rock phosphate + limestone.....	216	-7	-4.8	16	0.31
423 Rock phosphate + dolomite.....	86	154	-2.4	9	0.40
424 Rock phosphate + MgCO <sub>3</sub> .....	-23	287	-2.4	7	0.46
425 Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> alone.....	30	10	-1.2	11	0.09
426 Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> + CaF <sub>2</sub> .....	189	17	-1.2	6	5.40§
427 Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> + CaF <sub>2</sub> + limestone.....	269	-1	-4.8	14	6.03§
428 Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> + CaF <sub>2</sub> + dolomite.....	120	141	-4.8	13	6.22§
429 CaHPO <sub>4</sub> alone.....	119	0.3	-3.6	4	0.13
430 CaHPO <sub>4</sub> + CaF <sub>2</sub> .....	115	-2	-3.6	8	3.75
431 CaHPO <sub>4</sub> + CaF <sub>2</sub> + limestone.....	262	10	-6.0	11	3.53
432 CaHPO <sub>4</sub> + CaF <sub>2</sub> + dolomite.....	150	130	-3.6	13	3.89
433 Ca(PO <sub>3</sub> ) <sub>2</sub> alone.....	34	2	-0.2	8	0.19
434 Ca(PO <sub>3</sub> ) <sub>2</sub> + CaF <sub>2</sub> .....	77	-0.7	-2.4	4	4.87
435 Ca(PO <sub>3</sub> ) <sub>2</sub> + CaF <sub>2</sub> + limestone.....	203	8	-4.8	10	3.30
436 Ca(PO <sub>3</sub> ) <sub>2</sub> + CaF <sub>2</sub> + dolomite.....	109	146	-4.8	13	3.77
437 Ca(PO <sub>3</sub> ) <sub>2</sub> + limestone¶.....	194	2	-3.6	11	0.26
438 Ca(PO <sub>3</sub> ) <sub>2</sub> + limestone**.....	226	0.5	-3.6	14	0.26
439 Ca(PO <sub>3</sub> ) <sub>2</sub> + dolomite**.....	67	133	-4.8	6	0.23

\* As pounds more than the respective leachings from 2,000,000 pounds of untreated soil, which were 195 for Ca; 76 for Mg; 13 for K; 42 for N, and 0.21 for F.

† The brown rock phosphate at the 2-ton rate and the equivalent single inputs of tri-, di-, and metacalcium phosphates, and of limestone and dolomite, and the calcium fluoride repetitions were incorporated full depth, as stipulated under "Incorporated Materials."

‡ Total input of 2,400 pounds of fluorine, or 4,932 pounds of CaF<sub>2</sub>.

§ Represents concentration greater than 1 p.p.m. in ground waters—such concentration was attained only after fourth annual incorporation of CaF<sub>2</sub>.

|| Represents concentration less than 1 p.p.m., but concentrations greater than 1 p.p.m. occurred after the seventh annual incorporation of CaF<sub>2</sub>.

¶ The limestone and dolomite were incorporated 2 months previous to the incorporation of the phosphate, alone and with supplements.

\*\* Mixed together 24 hours before incorporation.

phosphate. Although the 98 per cent retention of the added fluorine may be attributable in part to the low dissolubility of CaF<sub>2</sub> in the drainage waters, that

retention is deemed attributable chiefly to the fixative capacity of the aluminous complexes in the soil.

The mean of the 10 annual migrations of fluorine from the tricalcium phosphate series represented a concentration beyond 1 p.p.m. in the drainage waters, yet that concentration was not attained in any yearly migration until four annual incorporations of  $\text{CaF}_2$  had been made. The incorporations of  $\text{CaF}_2$  did not induce a concentration of 1 p.p.m. of fluorine in any annual leaching from the dicalcium phosphate series until the annual leachings were from aggregates of seven incorporations of the fluoride.

### *Experiment II*

*Incorporations.* Three soils were used in this 12-year project under the title "The Migration, Fixation, Availability and Nature of the Combinations That Ensur When  $\text{P}_2\text{O}_5$  Is Supplied to the Soil by Acid Phosphate, with and Without Supplements of Limestone and Dolomite." The two acidic soils used are designated, in tables 3 and 4, as Cumberland silt loam and Sequoia silt loam, respectively, and the virtually neutral soil is designated as Calhoun silt loam, in table 5. Every soil placement was divided into three strata of equal depth, and the limestone and dolomite then were incorporated into the topmost stratum at a rate of 1 ton of  $\text{CaO}$  per acre surface. Seven months later the initial incorporation of the eleven 96-pound incorporations of  $\text{P}_2\text{O}_5$  was made as monocalcium phosphate solely in that stratum, and the acidity of every repetition was offset through supplements of limestone or of dolomite, in amounts respectively requisite to effect transitions of the primary phosphate to secondary state. Monocalcium phosphate was used instead of superphosphate to eliminate any effect from component  $\text{CaSO}_4$ , so that the enhancements in calcium migrations could be attributed to the phosphate-limestone and phosphate-dolomite combinations. The annual incorporations of rock phosphate and of monomagnesium phosphate were also in equivalence to the eleven annual incorporations of monocalcium phosphate.

A particular objective of this experiment was to learn whether the migration of phosphorus would be the same from equivalent inputs of that element in soils (a) wherein the limestone and dolomite had been allowed to undergo disintegration prior to the incorporation of the phosphates and (b) wherein corresponding mixtures of the monocalcium phosphate with either limestone or dolomite were incorporated after the respective mixtures had been allowed 24 hours to undergo substantial percentage transitions to dibasic state. An additional feature was to ascertain the extent to which a 2-inch layer of clay subsoil might alter the concentration of solutes in the leachings from the top-zone incorporations. The 12-year migrations of calcium, magnesium, potassium, and phosphorus from the three soils are shown in tables 3, 4, and 5.

*Migrations from Cumberland silt loam.* In every instance in table 3, save one, there was a small migration of phosphorus from the 1,056-pound cumulative inputs of  $\text{P}_2\text{O}_5$  as monocalcium and monomagnesium phosphates, when the leachings had not passed through the 2-inch layer of subsoil. In contrast, the rock



phosphate induced no increase in the outgo of either phosphorus or calcium and caused some decrease in the leachings of magnesium and of potassium. Such

TABLE 3

*Aggregates for 18 annual migrations of phosphorus, Ca, Mg, and K from 11 annual incorporations of monocalcium phosphate in the limestoned and dolomited upper-third zone of Cumberland silt loam*

INCORPORATED MATERIALS	TOTAL MIGRATION PER 2,000,000 POUNDS OF SOIL			
	Calcium as CaCO <sub>3</sub> - equivalence	Magnesium as CaCO <sub>3</sub> - equivalence	Potassium as K <sub>2</sub> O	Phosphorus as P <sub>2</sub> O <sub>5</sub>
	<i>lb.</i>	<i>lb.</i>	<i>lb.</i>	<i>lb.</i>
None, soil alone.....	2244	766	256	0.93
None, soil and 2-inch subsoil.....	2242	968	218	1.32
Monocalcium phosphate alone*.....	2559	742	263	1.24
Monocalcium phosphate directly into limestoned zone†.....	3898	594	198	1.34
Monocalcium phosphate directly into dolomited zone†.....	3355	2013	210	1.55
Monocalcium phosphate-limestone mixture‡.....	3670	558	190	0.82
Monocalcium phosphate-dolomite mixture‡.....	2428	1731	197	1.16
Monocalcium phosphate in previously limestoned zone† 2-in. subsoil.....	2860	760	155	0.89
Monocalcium phosphate in previously dolomited zone† 2-in. subsoil.....	2143	1353	151	0.88
Rock phosphate alone, in equivalence to P <sub>2</sub> O <sub>5</sub> , incorporated as in*.....	2178	670	234	0.88
Monomagnesium phosphate alone, in equivalence to P <sub>2</sub> O <sub>5</sub> , incorporated as in*.....	2074	903	240	1.50

\* Every total input of 1,056 pounds of P<sub>2</sub>O<sub>5</sub> was through 11 annual  $\frac{1}{2}$ -depth 96-pound incorporations, each of which was equivalent to 600 pounds of 16 per cent superphosphate per acre surface.

† The limestone and dolomite incorporations were made in the top zone at rate of 2,000 pounds CaO-equivalence per acre surface, 7 months before the incorporation of the phosphate.

‡ The mixtures were made 24 hours before incorporation—CO<sub>2</sub> evolution from the limestone mixtures registered complete transition to dicalcium phosphate against the 70 per cent transitions effected by the dolomite. Every subsequent input of monocalcium phosphate was accompanied by either limestone or dolomite in quantity sufficient to effect transition to dibasic state.

decrease in outgo of magnesium, and of potassium, was induced by the input of every calcic material.

Even though the phosphorus migrations were small, those from the phosphates

in the prelimestoned and predolomited soils exceeded the migrations from the phosphates that were incorporated by means of the respectively corresponding mixtures. A similar relationship obtains as to the larger migrations of calcium and magnesium from the prelimestoned and predolomited soils. The state of the phosphorus content of the phosphated stratum and the retentions within the two lower strata are reflected by the quantities of the several components of the leachates, without distinction between the retentions effected by those strata. To answer the question whether phosphorus enrichments in the leachings from

TABLE 4

*Aggregates for 12 annual migrations of phosphorus, Ca, Mg, and K from 11 annual equivalent incorporations of monocalcium phosphate in the limestoned and dolomited upper-third zone of Sequoia silt loam*

INCORPORATED MATERIALS	TOTAL MIGRATION PER 2,000,000 POUNDS OF SOIL			
	Calcium as CaCO <sub>3</sub> - equivalence	Magnesium as CaCO <sub>3</sub> - equivalence	Potassium as K <sub>2</sub> O	Phosphorus as P <sub>2</sub> O <sub>5</sub>
	lb.	lb.	lb.	lb.
None.....	2230	929	169	0.95
Monocalcium phosphate alone*.....	2336	953	168	1.91
Monocalcium phosphate directly into the lime- stoned zone†.....	4149	909	140	1.22
Monocalcium phosphate in dolomited zone†.....	3098	1460	134	1.74
Monocalcium phosphate-limestone mixture‡.....	3840	967	137	1.73
Monocalcium phosphate-dolomite mixture‡.....	3165	1509	138	1.94
Rock phosphate alone, in equivalence to*.....	2367	915	168	1.08

\* Every total input of 1,056 pounds of P<sub>2</sub>O<sub>5</sub> was through 11 annual  $\frac{1}{4}$ -depth 96-pound incorporations, each of which was equivalent to 600 pounds of 16 per cent superphosphate per acre surface.

† The limestone and dolomite incorporations were made only on the top zone, at rate of 2,000 pounds CaO-equivalence per acre surface, 7 months before the incorporation of the phosphate.

‡ The mixtures were made 24 hours before their incorporation—100 per cent transition to dibasic form by the limestone and 70 per cent by the dolomite. Every successive input of the monocalcium phosphate was accompanied by either limestone or dolomite, in quantity sufficient to effect transition to dibasic state.

the phosphated stratum were stopped fully by the middle stratum of unphosphated soils, plants were grown in greenhouse cultures of the upper, middle, and lower strata after the lysimeter phase of the 12-year experiment had been terminated (23). Through plant response and phosphorus uptake, these cultures demonstrated that significant enrichment of phosphorus in the middle stratum occurred only where the dibasic forms had been produced in the surface stratum through action by the liming materials, and that the migrations of phosphates did not extend to the bottom stratum.

*Migrations from Sequoia silt loam.* Every cumulative input of monocalcium phosphate induced a small, yet significant, increase in the leachings of phosphorus through the two lower strata. In contrast, the equivalent input of rock phosphate induced virtually no such increase. In the prelimestoned and predolomited series, and also in the corresponding mixture-input series, the dolomite

TABLE 5

*Aggregates for 12 annual migrations of phosphorus, Ca, Mg, and K from 11 annual equivalent incorporations of monocalcium phosphate in the upper third of Calhoun*

INCORPORATED MATERIALS	TOTAL MIGRATION PER 2,000,000 POUNDS OF SOIL			
	Calcium as $\text{CaCO}_3$ - equivalence	Magnesium as $\text{CaCO}_3$ - equivalence	Potassium as $\text{K}_2\text{O}$	Phosphorus as $\text{P}_2\text{O}_5$
	lb.	lb.	lb.	lb.
None.....	2783	709	202	5.54
Monocalcium phosphate alone*.....	2894	1014	203	7.37
Monocalcium phosphate directly into limestoned zone†.....	4271	751	187	31.74
Monocalcium phosphate directly into the dolomited zone‡.....	3302	1356	190	41.86
Monocalcium phosphate-limestone equivalent to* through mixture‡.....	4209	713	188	26.61
Monocalcium phosphate-dolomite equivalent to‡ through mixture‡.....	3217	1278	187	32.04
Rock phosphate alone, in equivalence to*.....	2756	880	188	4.26
Monomagnesium phosphate alone, in equivalence to*.....	2690	921	199	16.88

\* The total input of 1,056 pounds of  $\text{P}_2\text{O}_5$  was through 11 annual  $\frac{1}{2}$ -depth 96-pound incorporations, each of which was equivalent to 600 pounds of 16 per cent superphosphate per acre surface.

† Limestone and dolomite incorporations were made at rate of 2,000 pounds  $\text{CaO}$ -equivalence, 7 months before the incorporation of the phosphate.

‡ The mixtures were made 24 hours before their incorporation—100 per cent conversion to dibasic form by the limestone and 70 per cent by the dolomite. Every successive input of monocalcium phosphate was accompanied by either limestone or dolomite in quantity sufficient to effect transition to dibasic state.

induced phosphate migrations greater than those from the monocalcium phosphate.

Calcium passage through the unlimed lower strata was increased slightly by the acidic phosphate and by rock phosphate and extensively by limestone and by dolomite. Both types of limestone effected repressions in the outgo of potassium, but the calcic materials did not induce diminutions in all of the leachings of magnesium. It is to be remembered, however, that solute content of

those leachings were subject to alteration through retentions and exchanges during passage through the two lower strata. Hence, the ultimate compositions of the leachings did not register contents identical to those of the solutions that obtained before they had migrated from the phosphated upper stratum. Earlier findings had demonstrated the distinction between the "reciprocal repression" (4, 6) exerted by calcic and magnesian materials within the zone of incorporation, in contrast to the base exchange reactions induced by the solutes from that zone during their passage through an underlying unlimed stratum of the same soil (3, 5, 7, 9).

*Migrations from Calhoun silt loam.* The migrations of phosphorus from Calhoun silt loam of near alkaline reaction were in marked contrast to the relatively meager migrations of that element from the other two soils of the same experiment. The experimental soil had the physical characteristics of Calhoun, which,

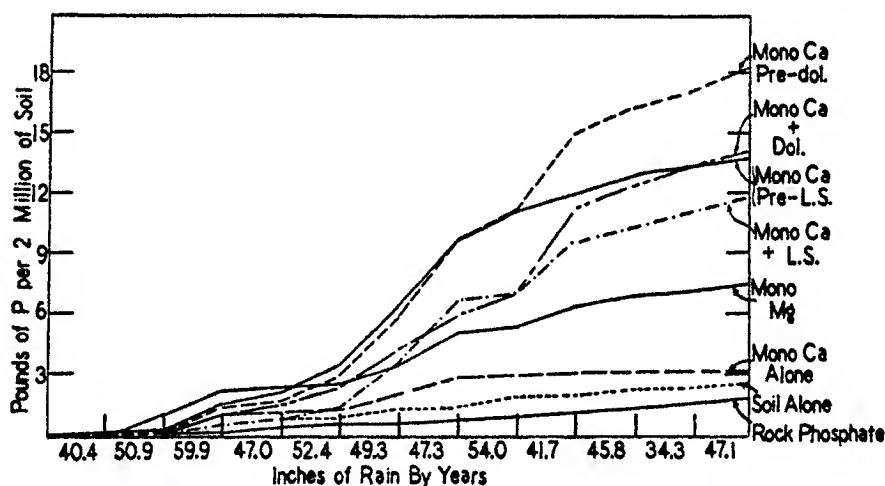


FIG. 1. Migrations of phosphorus induced by eleven 42-pound annual incorporations as monocalcium phosphate in prelimestone and predolomited soil and from corresponding premixtures in upper third of Calhoun silt loam during 12 years.

however, usually is classified as acidic, and it may be that the experimental soil was from a field that had been limed. The transitions induced by limestone and by dolomite were reflected by the outgo aggregates given in table 5 and by the cumulative migrations shown in figure 1.

The enriched leachings from the upper stratum of this soil were collected after they had gravitated through the underlying strata that were near-alkaline, whereas the leachings from the Cumberland and Sequoia soils had to pass through two underlying unlimed strata. Nevertheless, the enhancement in the migration of phosphorus through the two lower strata of the near-neutral Calhoun soil was increased thirteenfold, along with the marked enrichment of calcium, in the drainage waters as a consequence of the additional quantity of calcium that was present in the prelimestone soil systems, whereas the migration of phosphorus from the predolomited soil was enhanced twentyfold.

The aggregate enhancement in the migration of phosphorus from the monomagnesium phosphate in the unlimestoned Calhoun soil was six times such enhancement from the corresponding incorporation of monocalcium phosphate. The curves of figure 1 show that, throughout the the initial 4 years, phosphorus migration from the magnesium phosphate invariably exceeded that from any of the four equivalent inputs of monocalcium phosphate that were made in association with limestone or with dolomite. Thereafter, the migration curve for the magnesium phosphate in the unlimed soil fell below the four curves for the calcium monophosphate that was incorporated either directly into the limestoned and dolomited units or by means of the mixtures of that phosphate with limestone and with dolomite. The greater accelerative effect of the dolomite, in comparison with the effect of limestone, upon the migration of phosphorus became more pronounced after eight annual incorporations had supplied 768 pounds of  $P_2O_5$ .

Some increase in calcium outgo was induced by the annual inputs of monocalcium phosphate to the unlimed Calhoun soil, but none was induced by the equivalent inputs of rock phosphate or of monomagnesium phosphate. The four limestoned and dolomited units that received monocalcium phosphate registered repression in potassium outgo, as did also the rock phosphate incorporation in the unlimed soil.

### Experiment III

*Incorporations.* In this experiment the analyses of leachings registered the migrations of phosphorus and associated elements from annual full-depth incorporations of phosphatic materials in two distinctive soils, without incorporations of liming supplements. Equivalent quantities of  $H_2PO_4$ , mono-, di-, and tricalcium phosphates, and Tennessee Valley Authority fused tricalcium phosphate of 100-mesh (table 6) were incorporated in acidic Hartsells fine sandy loam each year. The companion near-neutral Dewey silt loam (table 7) received equivalent annual incorporations of  $H_2PO_4$ , and of monoammonium and diammonium phosphates, the control for their nitrogen content being supplied through an equivalence of ammonium sulfate.

*Migrations from Harsells soil.* The 10-year aggregates of the migrations from this fine sandy loam are given in table 6. The quantities of phosphorus that passed from the full-depth inputs of either  $H_2PO_4$  or the T.V.A. fused tricalcium phosphate were meager, although appreciable quantities of that element did pass from the inputs of the primary and tertiary phosphates of calcium. The dicalcium phosphate induced the maximal migration of 101 pounds of  $P_2O_5$ , and the curves in figure 2 show that the marked enhancement in outgo occurred after the fifth year. The input of  $P_2O_5$  then had amounted to 1,600 pounds and the concomitant calcium had served to diminish the inherent acidity of the soil.

The incorporations of  $H_2PO_4$  caused a decrease in calcium outgo below that from the untreated soil. Hence, a portion of the calcium that would have appeared in the normal drainage waters evidently reacted with the added acid. The larger proportion of the  $H_2PO_4$  apparently underwent fixation by Fe and Al complexes, since the equivalent input of the monocalcium phosphate induced a

large increase in the calcium outgo. The enhancements in overall outgo of calcium from the three calcium phosphates of table 6 were in the same order of

TABLE 6

*Aggregate migrations\* of phosphorus and associated elements from nine annual incorporations of  $H_2PO_4$  and four calcic phosphates in acidic Hartselle fine sandy loam*

INCORPORATED MATERIALS†	10-YEAR TOTALS PER 2,000,000 POUNDS OF SOIL										
	Calcium as $CaCO_3$ - equivalence		Magnesium as $CaCO_3$ - equivalence		Potassium as $K_2O$		Sulfur as $SO_2$		Nitrate N		Phosphorus as $P_2O_5$
	Total	Dev.‡	Total	Dev.‡	Total	Dev.‡	Total	Dev.‡	Total	Dev.‡	Total
	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.
None.....	1496	—	353	—	166	—	957	—	325	—	—
$H_2PO_4$ .....	1410	-86	358	5	145	-21	1022	65	301	-24	1.05
Monocalcium phosphate.....	2278	777	285	-68	127	-89	1149	192	405	80	9.32
Dicalcium phosphate....	2896	1400	253	-100	83	-83	1085	128	486	161	101.20
Tricalcium phosphate....	2706	1210	302	-51	85	-81	1178	221	452	127	12.25
Fused tricalcium phosphate.....	1870	374	287	-66	135	-31	1077	120	337	12	0.98

\* Induced by rainwaters, average of 48 inches per annum during 10 years.

† The nine annual full-depth incorporations supplied 2,880 pounds of  $P_2O_5$ .

‡ Deviation from the untreated soil control.

TABLE 7

*Aggregate migrations\* of phosphorus and associated elements from nine annual incorporations of  $H_2PO_4$  and two ammonium phosphates in near-neutral Dewey silt loam*

INCORPORATED MATERIALS†	10-YEAR TOTALS PER 2,000,000 POUNDS OF SOIL										
	Calcium as $CaCO_3$		Magnesium as $CaCO_3$		Potassium as $K_2O$		Sulfur as $SO_2$		Nitrogen		Phosphorus as $P_2O_5$
	Total	Dev.‡	Total	Dev.‡	Total	Dev.‡	Total	Dev.‡	Total	Dev.‡	Total
	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.
None.....	4113	—	974	—	145	—	1133	—	708	—	0.83
$H_2PO_4$ .....	3740	-373	897	-77	118	-27	1104	-29	614	-94	109.54
Monoammonium phosphate.....	5245	1132	1103	129	148	3	1128	-5	1197	489	143.95
Diammonium phosphate....	6352	2239	1193	219	134	-11	1141	8	1602	894	77.72
Ammonium sulfate.....	10503	6390	1564	590	269	124	5398	4265	2158	1450	2.26

\* Induced by rainwaters, average of 48 inches per annum during 10 years.

† The nine annual full-depth phosphate incorporations supplied 2,880 pounds of  $P_2O_5$ .

‡ Deviation from untreated soil control.

|| Includes outgo of N in forms of  $NH_3$  and  $NO_3$ .

¶ Represented 78.8 per cent of the 4,869-pound input of  $SO_2$ .

magnitude shown for the concomitant migrations of phosphorus. Obviously, this registers the respective extents to which dicalcium phosphate passed into the solute phase of secondary calcium phosphate in the free soil-waters of the

## PHOSPHORUS FERTILIZERS IN SOILS

severally phosphated soil systems. Although the fused tricalcium phosphate caused no increase in the outgo of phosphorus, some of that product evidently underwent dissolution in the soil, since it induced a 374-pound increase in the outgo of calcium and a depression in the companion outgo of magnesium.

The  $H_2PO_4$  effected a decrease in the outgo of potassium, and every phosphate of calcium induced a significant decrease in the outgo of both potassium and magnesium. Increase in the outgo of sulfur was induced by every phosphatic material, whereas nitrification was increased significantly only by the three phosphates of calcium, the largest outgo of nitrates being that attributable to the dicalcium phosphate.

*Migrations from Dewey soil.* The incorporated  $H_2PO_4$  registered a different behavior in near-neutral Dewey silt loam, which contained a good native supply

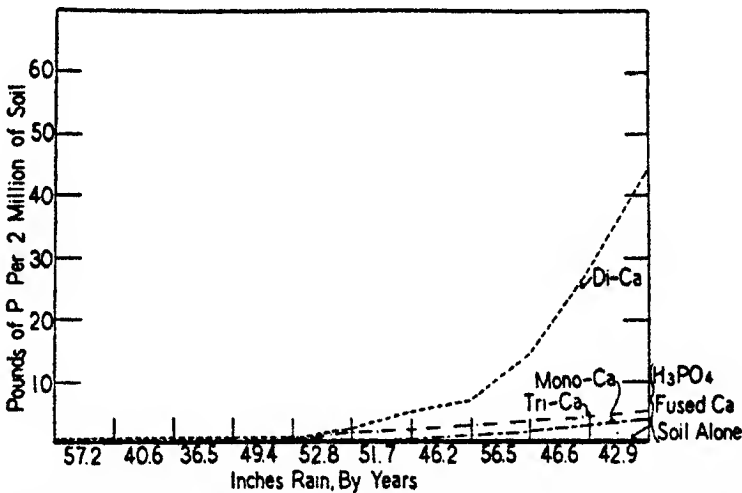


FIG. 2. Migrations of phosphorus induced by nine annual full-depth incorporations of  $H_2PO_4$ ; mono-, di-, and tricalcium phosphates; and fused tricalcium phosphate in acidic Hartsells fine sandy loam during 10 years.

of calcium. The substantial migration of phosphorus from nine annual full-depth incorporations of that acid stands in marked contrast to the nugatory passage from such incorporations in the acidic Hartsells soil. The maximal outgo of 149-pounds of  $P_2O_5$  was induced by the monoammonium phosphate. The curves of figure 3 show, however, that the large increase in the passage of phosphorus from that phosphate came after the first four annual incorporations had supplied 384 pounds of  $P_2O_5$ . Although the overall outgo of phosphorus from  $H_2PO_4$  surpassed the total outgo from the diammonium phosphate, the difference developed only after the sixth annual 96-pound incorporation of  $P_2O_5$ .

Again, however, the  $H_2PO_4$  lessened the outgo of calcium, of magnesium, of potassium, of sulfur, and of nitrogen. The diminished migration of calcium from the  $H_2PO_4$  is 1,505 pounds less than the  $CaCO_3$ -equivalence of the enhanced outgo from monoammonium phosphate, whereas there was a difference of

only 39 pounds in the migrations of  $P_2O_5$ . The outgo of calcium in the leachings from the diammonium phosphate inputs was twice the outgo in the leachings from the inputs of monoammonium phosphate. The larger outgo of calcium from the phosphate of higher nitrate potential, and the still greater outgo of calcium from the incorporations of ammonium sulfate, are reflected by the larger leachings of nitrates and also by the quantities of nitrites that passed from the inputs of the three ammoniacal compounds.

Magnesium outgo was enhanced by the mono- and diammonium phosphates, in that order, and to maximal extent by the  $(NH_4)_2SO_4$ . The two phosphates of ammonium exerted small overall effects upon the outgo of potassium, whereas the nitrogen-equivalent sulfate induced a substantial increase in the leachings of that element. The increase of the outgo of sulfur from the ammonium sulfate represented a 78.8 per cent recovery of the input of that element.

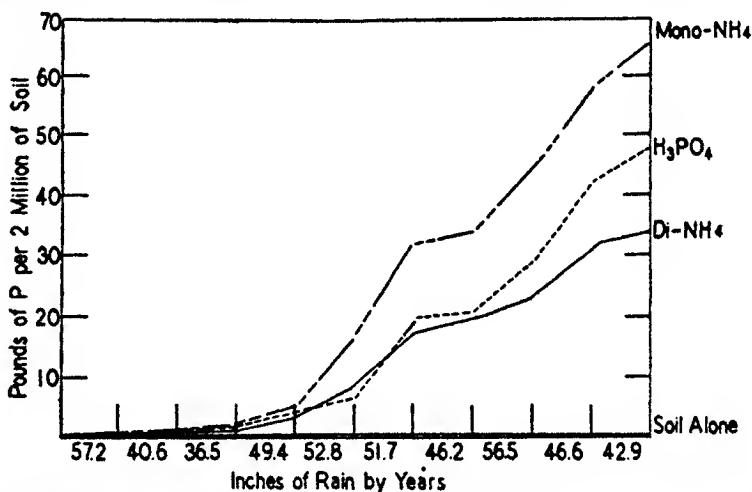


FIG. 3. Migrations of phosphorus induced by nine annual full-depth incorporations of  $H_3PO_4$  and mono- and diammonium phosphates in near-neutral Dewey silt loam during 10 years.

#### DISCUSSION AND INTERPRETATIONS

The findings from the 10-year experiment of table 1 established the fact that phosphate migration from Clarksville silt loam—unlimed, limed, or dolomited—was not measurably increased when the phosphorus content was augmented by 1,280 pounds of  $P_2O_5$  through the single, full-depth incorporation of rock phosphate and through equivalent separate incorporations of mono-, di-, and triphosphates of calcium. Because of the meager outgo of phosphorus from every phosphated soil system, there was no indication as to whether the 10 annual incorporations of  $CaF_2$  exerted different effects upon the "availability" of the several incorporated phosphates.

Likewise the capacity of the Clarksville soil to retain the phosphorus of the full-depth incorporations of the primary, secondary, and tertiary calcic phosphates was such that no distinction in specific effects upon phosphorus avail-



ability was registered for the liming materials or for the repetitive inputs of calcium fluoride. It may be that the possible differential effects of those supplements upon the several types of phosphate can be established through pot cultures and chemical extractions.

Obviously, the significantly larger outgo of calcium, of magnesium, and of fluorine from the tertiary phosphate registers a differential reactivity for that material. In every instance, however, an input of calcium caused decrease in the outgo of potassium, whereas the sole addition of magnesium carbonate induced a decrease in the outgo of both potassium and calcium.

In the 12-year experiment, a similar retention of phosphorus was registered by the two distinctly acidic soils of the three that received eleven annual incorporations of monocalcium phosphate solely into the upper-third stratum, wherein incorporations of limestone and dolomite had been "aged" 7 months and wherein similar incorporations were made through their mixtures with the initial input of the monocalcium phosphate. Again the phosphate-retention capacity of the unlimed lower-two-third zone of each acidic soil was such as to inhibit significant increase of phosphorus in the leachings from the rock phosphate incorporations, or from those of monocalcium phosphate, which provided an overall input of 1,056 pounds of  $P_2O_5$  through eleven annual incorporations.

In contrast, the upper-stratum incorporations of the primary phosphates of calcium and magnesium induced considerable migrations of phosphorus through the lower-two-third zone of the near-neutral Calhoun soil. The greater mobility of dimagnesium phosphate was indicated in every comparison, since every phosphorus outgo induced by dolomite exceeded the phosphorus outgo induced by limestone. The relative inertness of the rock phosphate was obvious, since the incorporations of raw rock induced no enhancement in the passage of either phosphorus or calcium.

The increase in the outgo of phosphorus from the monocalcium in the near-neutral, experimentally unlimed Calhoun soil was decidedly less than the increase from the equivalent input of monomagnesium phosphate. It is evident that the enhancement in migration of calcium from the treated top stratum served to decrease markedly the capacity of this soil to effect fixation of phosphorus in the underlying two-third zone. Moreover, this diminution in capacity to effect phosphatic fixation was decreased still further through the migration of the substantial quantities of magnesium that were released by the dolomite to the leachings.

The distinctive properties of the two soils of the third experiment are reflected by the marked disparity in their released phosphorus from the nine annual inputs of  $H_3PO_4$ , full-depth. Although the acidic Hartsells soil yielded virtually no enhancement in the outgo of phosphorus from such inputs, the Dewey soil yielded a substantial outgo of that element. In both soils, however, the added  $H_3PO_4$  caused diminution in the migrations of calcium and potassium.

The retention of phosphorus from the  $H_3PO_4$  in the acidic Hartsells soil was in contrast to the considerable outgo of that element from the monocalcium and tricalcium phosphates. In even greater contrast was the maximal migration of phosphorus from the dicalcium phosphate, the marked increase having come

after the fifth annual incorporations. Although the fused tricalcium phosphate induced no increase in the migration of phosphorus, that material did undergo some dissolution in the soil, since it did induce a considerable increase in the outgo of calcium, and of sulfur, while effecting decreases in the leachings of magnesium and potassium. Decreases in the outgo of magnesium and of potassium from the Hartsells soil were induced by the primary, secondary, and tertiary phosphates of calcium.

Since the Dewey soil contained a good supply of calcium, the incorporations of phosphorus were supplied to that soil by means of the acid-potential phosphates of ammonium, in lieu of the several phosphates of calcium. The mono-ammonium phosphate induced the maximal migration total of 149 pounds of phosphorus, along with substantial enhancements in the outgo of calcium and of magnesium. That aggregate for phosphorus migration was twice the aggregate induced by the diammonium phosphate. The decided increases in phosphorus migration came, however, after the fourth year, for respective passages from the mono salt,  $\text{H}_2\text{PO}_4$ , and the diammonium salt, in that order of magnitude.

The greater proportion of  $\text{NH}_4$  in the diammonium salt caused doubled migrations of both calcium and magnesium. The effect of the nitrification of the  $\text{NH}_4$  is reflected also by the decidedly larger leachings of calcium, magnesium, and potassium from the ammonium sulfate control, which supplied the nitrogen equivalence of the diammonium phosphate.

Although appreciable concentrations of phosphorus developed in the leachings from the inputs of the several acidic phosphates in the limed soils, and in the two soils of the third experiment in particular, it does not follow that such migrations would have occurred had shallow-rooted plants been grown in the severally phosphated soils. An abundance of readily available phosphorus would tend to stimulate plant growth, and the phosphorus content of the leachings then would be diminished through a greater uptake, even to the extent of "luxury consumptions." In absence of plant growth, the migrations of phosphorus and associated elements serve as an index to (a) the several transitions that occurred in the variously phosphated systems, (b) extent of, and variance in, phosphorus fixations, (c) fate and influence of the different supplements, (d) comparative mobility of phosphates of calcium and magnesium, (e) the greater mobility of dimagnesium phosphate either added or engendered, (f) the greater mobility of phosphorus supplied to prelimed soils in comparisons with corresponding premixtures, and (g) degree of exertion that would be required for plants to obtain an adequate supply of phosphorus and attendant elements. Since the migrations register the ready mobility of the engendered dicalcium phosphate, especially that engendered within the soil, and the still greater mobility of the soil-engendered dimagnesium phosphate, the migrations register also the "availability" of those phosphates and the facility with which growing plants could obtain phosphorus.

The responsiveness of plants to incorporations of  $\text{H}_2\text{PO}_4$  was studied at the Tennessee Experiment Station (21). Use of  $\text{P}_2\text{O}_5$ -impregnated orthophosphoric acid, of 82 per cent  $\text{P}_2\text{O}_5$  content, might be more economical than use of the usual furnace-made product of 62.5 per cent  $\text{P}_2\text{O}_5$  content.

The downward movement of the phosphorus of commercial fertilizers, and of rock phosphate, has been studied by means of analyses of successive soil horizons, as in work reported by Bryan (2), Robinson and Jones (26), and many others. Recently Neller (25) reported a small-scale study of the phosphorus content of leachings of phosphorus from additive phosphates in Florida sandy soils.

So far as known to the authors of this paper, mobility of phosphoric acid and differential migrations of the several phosphates of calcium, magnesium, and ammonium have not been studied heretofore through long-time lysimeter experiments. The several objectives and duration of the present experiments have afforded opportunity to determine the behavior of single additions of equivalent inputs of various types of calcic phosphates, when these were subjected to immediate and to delayed additions of potentially alternative material. The studies also afforded opportunity to ascertain the mobilities of the phosphorus of the cumulated inputs of the various phosphates in early and successive periods.

As over-all conclusions for application to humid regions, it appears that the fate and conservation of additive phosphates are governed by several factors: (a) incorporation of calcium fluoride at abnormal rates and a cumulative build-up of fluorine do not induce measurable variations in the passage of phosphates from substantial inputs of the several phosphates of calcium, (b) the type of phosphate should be specific for a particular soil, in relation to its initial reaction and to its reaction subsequent to incorporations of limestone or of dolomite, (c) conditions conducive to the formation and maintenance of dicalcium and dimagnesium phosphates in the soil system serve to prolong a higher degree of phosphorus availability, (d) those conditions are induced more effectively by dolomite than by limestone, (e) effective preliming of an acidic soil is conducive to a better degree of phosphate mobility and availability of the phosphorus incorporated in acidic state, and (f)  $H_2PO_4$ , monomagnesium phosphate, and monoammonium phosphate react advantageously in soils of adequate calcium supply.

The continuation of incorporated fertilizer phosphorus in combinations readily utilizable by plants is governed by how appropriate the type of the incorporated phosphorus is to a specific soil of adequate alkaline-earth content, either natural or provided through judicious liming with limestone or dolomite.

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# SIPHON DRAINAGE IN THE HYDE-PARK-BENSON AREA, CACHE VALLEY, UTAH

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Drainage of waterlogged saline soil near Hyde Park, in Cache Valley, Utah, has been under investigation for a considerable time. The Humpherys Brothers, engineers for the district at one time, made a study of this problem. Israelsen and McLaughlin<sup>2</sup> proposed methods of drainage and pointed out significant results that would follow.

Research men are agreed that the drainage of these lands would restore the soil to a condition suitable for plant growth, but it is vital that careful consideration be given to the problem of design. The geological formation, with the artesian ground-water reservoir in the area under consideration, constitutes a unique situation in which the siphon drain may function to good advantage. It is the essential purpose of this article to point out a method of drainage that should prove effective.

## THE SOIL PROFILE AND ARTESIAN AQUIFER

The soil under consideration is in process of formation on deep alluvial clay overlying a gravel aquifer which is 40 to 50 feet below the surface. The topography in the region is such that water from the mountains drains constantly into the gravel. This stratum pinches out, however, toward the west end of the tract, and for that reason hydrostatic pressure develops. As a direct consequence, a serious condition of waterlogging has developed.

Because of the impermeability of the clay, tile drains manifestly will not correct this condition. Data presented by Israelsen and McLaughlin confirm this view.

## DRAINAGE WELLS

Obviously, the hydrostatic pressure must be relieved. This may be accomplished, of course, by pumping on a large scale, but in this locality a siphon drain may function to good advantage and, it is believed, would cost much less. Because of the difficulty of determining in advance the amount of water that must be removed, it will be impracticable to complete the design either for pumping or for drainage by siphoning. It is proposed, however, to construct one artesian well to yield approximately 10 cubic feet of water per second and a second smaller well at a lower elevation to yield approximately 5 cubic feet per

<sup>1</sup> Graduate student, Department of Physics, Utah State Agricultural College. Paper approved for publication by the director, September 29, 1948.

<sup>2</sup> Israelsen, O. W., and McLaughlin, W. W. Drainage of land overlying an artesian groundwater reservoir. Utah Agr. Exp. Sta. Buls. 242 (1932) and 259 (1935).

second. Should these prove to be inadequate, additional wells may, of course, be installed.

The large well (No. 1, fig. 1) is near an irrigation canal approximately 4,000 feet west of Highway 91. The small well (No. 2) is approximately 8,448 feet northwest of Well 1. About 3,500 feet beyond to the northwest, lies a deep ravine approximately 14 feet below the surface of the ground at Well 2. The design provides for a sump with an air-tight pipe to carry the drainage water into

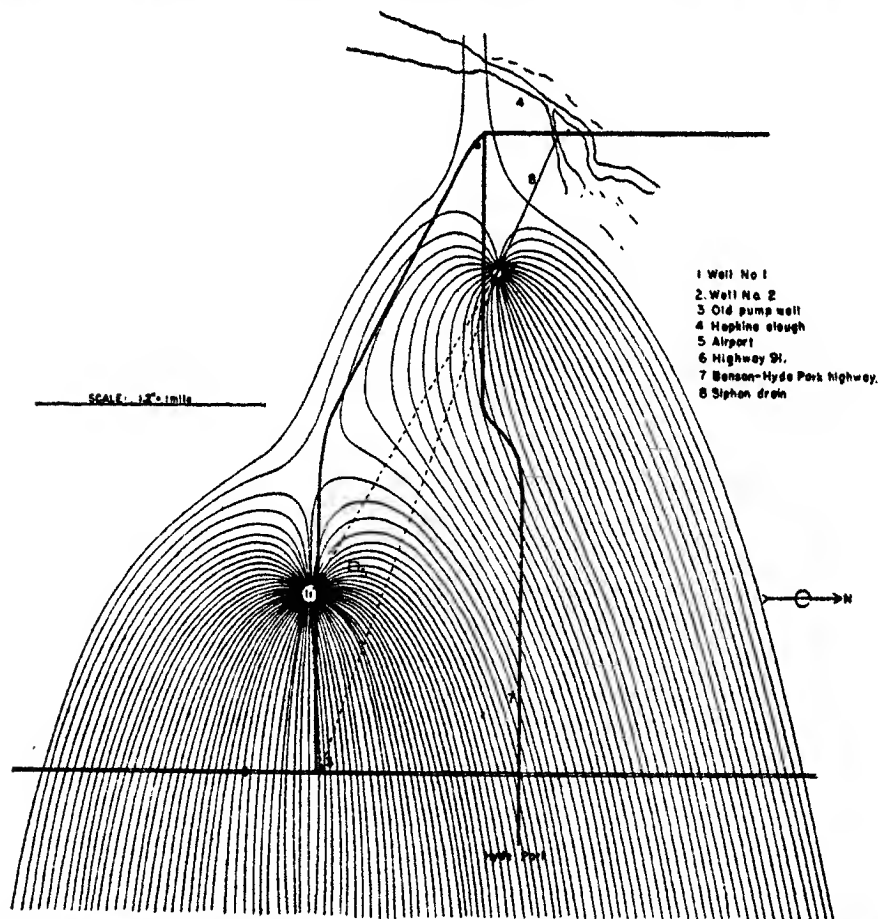


FIG. 1. GENERAL NATURE OF DISTRIBUTION OF STREAMLINES INTO PROPOSED WELLS 1 AND 2 IN SIPHON DRAINAGE PROJECT

the ravine designated as *Hopkins slough* in figures 1 and 3. The sump functions as an air-tight connection between the wells and the drain. A similar design is provided for Well 1, except that an open channel replaces the air-tight pipe and leads directly into a canal a short distance away.

Pumps may, of course, be installed in both sumps. These would provide irrigation water and at the same time increase the suction on the flowing wells. The underlying theory of this plan of drainage contemplates lowering the piezo-

metric surface below the surface of the ground. This will stop the upward flow through the clay and will at the same time enable the irrigation water to penetrate the soil and move slowly downward. From the standpoint of drainage alone, a pump would perhaps be unnecessary for Well 2, although it would provide irrigation water for adjacent land if required.

It is assumed that the stream that flows constantly westward through the artesian stratum in the locality under consideration is approximately 15 cubic feet per second and that therefore the wells should be designed to produce this amount of water. The streamline pattern of figure 1 is based on the assumption that Well 1 produces twice as much as Well 2, and that the two combined take care of the water in the gravel stratum for a width of about  $3\frac{1}{2}$  miles measured along Highway 91.

In mapping the streamline pattern the two wells were assumed to lie in a horizontal stratum in which the pressure is uniform. The resultant stream pattern of these two was drawn and this, in turn, was superimposed upon the uniform flow from east to west. On the other hand, the well radii were computed from the analytical theory of the Darcy law by disregarding the uniform flow from east to west. The error thus introduced would perhaps not be serious.

The Darcy equation may be written,

$$v = -k\nabla h, \quad (1)$$

and the equation of continuity,

$$q = 2\pi rLv, \quad (2)$$

$v$  representing the velocity,  $h$  the hydraulic head,  $k$  the permeability,  $q$  the size of the stream,  $r$  the radius of the random circle centered at the well, and  $L$  the thickness of the artesian stratum. On the basis of experimental data obtained by Morgan and Israelsen<sup>3</sup> and others, the permeability factor  $k$  of the gravel is taken to be equal to 0.016 feet per second and the thickness of the gravel stratum 15 feet. From these data we obtain

$$2\pi LK = 1.5 \frac{\text{feet}^2}{\text{second}} \quad (3)$$

and by combining equations (1), (2), and (3), and integrating, we obtain

$$\ln r/r_0 = \frac{1.5}{q} (h - h_0). \quad (4)$$

If the head loss ( $h - h_0$ ) is regarded as one parameter and the distance  $r$  from one or the other of the two wells as a second parameter, equation (4) may be regarded as a relation between the radius  $r_0$  of a well and the size of the stream  $q$ . A value of  $r$  for each of two sets of three values of the head loss was selected, and two sets of curves were thus obtained, as shown in figure 2. The three values of

<sup>3</sup> Morgan, R. E., and Israelsen, O. W. The water conductivity of an artesian aquifer. *Utah Acad. Sci., Arts and Letters Proc.* 11: 11-13. 1934.

$(h - h_0)$ , 16, 19, and 22 feet, are represented for a value of 8,448 feet for  $r$ ; and three values, 21, 23, and 25 feet for a value of 4,000 feet for  $r$ .

The elevations of the ground surface referred to Well 2 as a base are: Well 1, 19.4 feet; Well 3, 42.4 feet; Hopkins slough, 14.0 feet. These data were taken

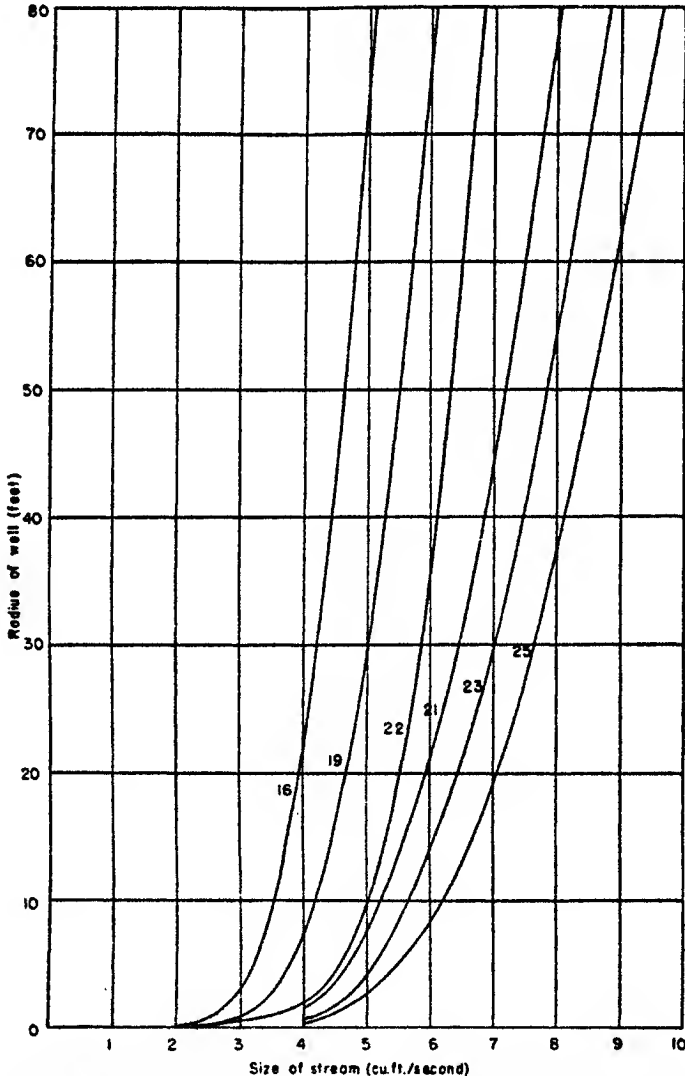


FIG. 2. RELATION BETWEEN SIZE OF WELL AND SIZE OF STREAM INVOLVING PARAMETERS EXPLAINED IN TEXT

into account, in connection with the analytical theory and the diagram of figure 2, and the effective radii of the two well networks were computed for arbitrary choices of head loss and for various sizes of stream. In the one case the head loss was between Well 2 and Well 1, and in the other between Well 3 and Well 1 (see Fig. 1).



Figure 4 illustrates the effect of increasing the size of pipe on the friction head loss. For example, if the drain pipe 3,500 feet long carries 6 cubic feet per second

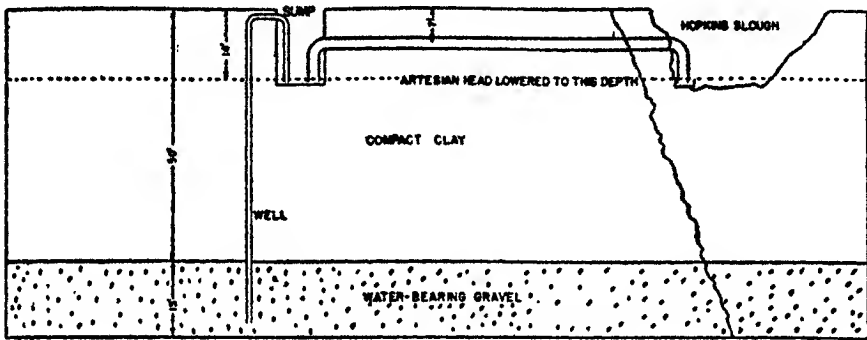


FIG. 3. DIAGRAM OF SIPHON DRAIN

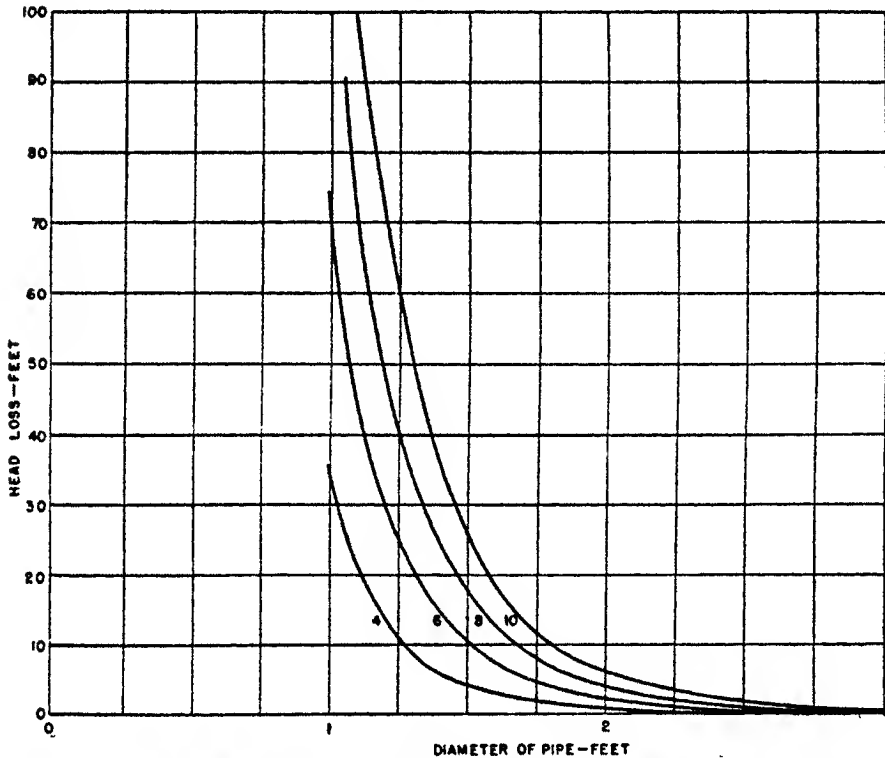


FIG. 4. DIAGRAM OF HEAD LOSS IN 3,500 FEET OF IRON OR CONCRETE PIPE AS A FUNCTION OF THE DIAMETER

Size of stream in cubic feet per second being the parameter.

and has a diameter of 1.5 feet, the loss of head is 11 feet, whereas if the diameter is increased to 2 feet this loss is reduced to 2.4 feet.

As has been pointed out, it would be difficult to design the ideal drainage sys-

tem without knowing more about the amount of water to be taken care of, boundary conditions, and other factors. It is apparent, however, that the large well near the canal will produce a large stream of irrigation water for the farmers in the region, and it is suggested that this well be constructed first. Additional valuable information will be obtained as a by-product. The concrete channel from the sump to the canal should be designed to reduce the loss in head to a practical minimum, and it is presumed that the piezometric surface in the immediate neighborhood of the well and also at remote points in the area will be below the surface of the ground.

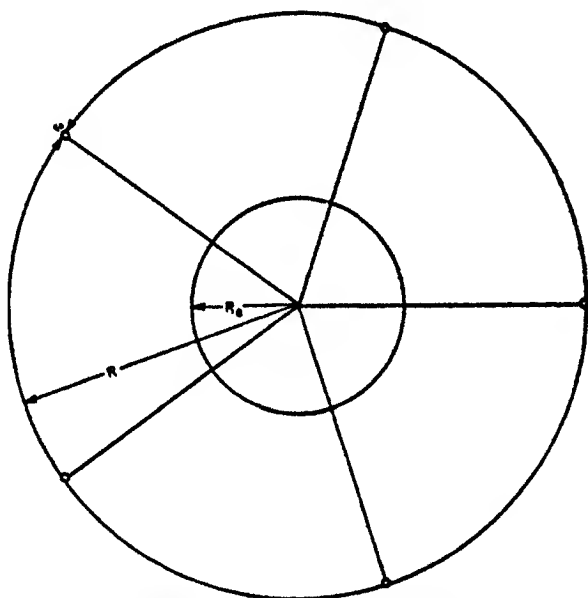


FIG. 5. SKETCH OF WELL NETWORK DESIGN

#### DESIGN OF WELLS

Gardner and Israelsen,<sup>4</sup> in discussing the design of drainage wells, have taken into account not only cost of power from friction loss in the artesian aquifer and in the pipes, but also the cost of pipe. For a stream of 5 cubic feet per second they propose constructing a circular array of five wells 7.2 inches in diameter with an additional well at the center. These wells are placed in a circle of radius 125 feet and the effective radius of the network is 45 feet. Figure 2 shows that for a stream of 5 cubic feet per second involving a loss in head of 19 feet from a point 8,448 feet from the well the radius of the well should be 30 feet. If we assume as a first approximation that the distance between two adjacent wells of a circular array is equal to the length of the arc of the circle connecting them and then impose the condition that the loss of head from a point midway between these two adjacent wells to either one of the wells is the same as the loss in head from this

<sup>4</sup> Gardner, W., and Israelsen, O. W. Design of drainage wells. Utah Engin. Exp. Sta. Bul. 1. 1940.

point to the circumference of the circle representing the effective radius,  $R_e$ , we may write the equations,

$$\ln R/R_0 = \frac{1.5}{q} (H - H_0) \quad (5)$$

$$\ln r/r_0 = \ln \frac{2\pi R}{2\pi r_0} = \frac{1.5}{q/n} (h - h_0) \quad (6)$$

and then equate the two head losses, thus,

$$H - H_0 = h - h_0 \quad (7)$$

or

$$\ln (R/R_0)^n = \ln \pi R / (\pi r_0) \quad (8)$$

which, when solved explicitly for  $R$ , becomes,

$$R = \left( \frac{\pi}{n r_0} \right)^{1/n-1} R_e^{n/n-1} \quad (9)$$

and this gives  $R$  as a function of  $R_e$ , with  $n$  and  $r_0$  as independent parameters,  $R$  being the radius of the circular array (fig. 5).

Following the lead of Gardner and Israelsen,  $n$  is taken equal to 5 and  $r_0$  to 0.33 feet. By substituting 30 feet for  $R_e$ , a value of 82.5 feet is obtained for the radius  $R$  of the circular array of wells that constitute the small well.

For the large well, we compute the radius  $R_0$  (or  $R_e$ ) with the help of equation (5), substituting  $q = 10$  cubic feet per second,  $r = 4,000$  feet, and  $H - H_0 = 25$  feet, and, with the help of equation (9), obtain for the radius of the circular array,  $R = 165$  feet.

These two wells with the sumps and their outlets constitute the tentative drainage system. As mentioned previously, additional wells may be required. It seems likely also that a pump should be used on the large well during the irrigation season.

#### SUMMARY

This paper gives an outline of a proposed siphon-connected drain system for relieving the hydrostatic pressure of an artesian aquifer beneath a tract of land in Cache Valley, Utah.

Figure 1 shows in a general way the nature of the distribution of the streamlines into the two wells proposed. Figure 2 illustrates the relation between the effective radii for the two wells and the size of stream. The head loss and distance from well are the parameters. Figure 3 shows one sump and siphon-connected drain. Figure 4 illustrates the head loss in terms of the size of the pipe, the size of stream being the parameter. Figure 5 illustrates the well network.



# SOIL CHARACTERISTICS SIGNIFICANT IN EVALUATING PERMEABILITY<sup>1</sup>

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Soil conservation surveys furnish basic land information needed for conservation farm planning. In soil conservation surveys, land is described in terms of characteristics that are significant in planning the use and treatment of farms. The soil-mapping units are separated chiefly on the bases of effective depth, texture of surface soil, and permeability of the subsoil and the substratum. Other factors such as slope, degree of erosion, overflow hazards, degree of wetness, character of substratum, available moisture capacity, and soil reaction are also mapped or described wherever they are significant in the use and treatment of land.

Effective depth—the depth of the soil material that plant roots can penetrate easily and from which they obtain water and nutrients—can be mapped consistently once the limits of each depth class are established. Soil texture also can be fairly accurately and consistently mapped through the use of field clues. These clues are the outgrowth of years of study in which soil scientists have developed a sensitive touch with respect to soil characteristics that correlate with definite percentages of sand, silt, and clay in soil samples. Soil permeability, on the other hand, is not yet easy to determine in the field. Little information is available on the correlation of permeability with soil characteristics.

The growing demand for precise information on soil permeability is not surprising when one considers the important role of percolating water in soil conservation. Information about permeability is essential for the functional classification of soils. A knowledge of the permeability of different soils is useful in planning the agronomic phase of the conservation program for a farm and in designing and spacing terraces for erosion control and water conservation. It is needed for adequate planning of drainage and irrigation systems and for the selection of sites for farm ponds. Also, it is essential in planning for flood control.

## DETERMINATION OF SOIL PERMEABILITY

Soil permeability may be defined as the capacity of the soil to transmit water and air. It can be expressed quantitatively in terms of rate of percolation of water through a column of soil under specific conditions. Rates of percolation

<sup>1</sup> Contribution from the Soil Conservation Surveys Division, Soil Conservation Service, U. S. Department of Agriculture. Presented before the Soil Conservation Society of America, Cincinnati, Ohio, December 11, 1948.

<sup>2</sup> Assistance is acknowledged of many persons in the Soil Conservation Service who made measurements of percolation rates and participated in development of field clues.

are usually expressed in inches per hour. A standard procedure has been adopted for measurements made in connection with soil conservation surveys.<sup>1</sup> A core sample 3 inches in diameter and 3 inches in length is taken in a metal cylinder with the least possible disturbance of natural structure and volume. Percolation under gravity and drainage of pores under tension are measured by a standard procedure that involves presaturation of the sample. The percolation rate may also be measured at field moisture content to give a better idea of probable performance under irrigation. The rates reported in this paper, however, are for percolation through saturated samples.

For precise expression of the permeability of a soil it is necessary to determine the permeability of each horizon to the depth desired. Sometimes a practical single expression is the permeability of the least permeable horizon in the subsoil or substratum. More often it is useful to state the permeability of both subsoil and substratum. This paper is concerned with permeability of soil horizons beneath the surface; not with the permeability at the immediate surface, which affects the rate of infiltration of natural or simulated rainfall.

Satisfactory determinations of permeability can be made on representative sites within the soil-mapping units that are described and mapped in surveys. But it probably never will be practicable to make as many measurements as would be needed to determine the complete range in permeability throughout the extent of all mapping units. Therefore, some scheme must be devised that will permit the extension of information ascertained from thoroughly studied control sites to other sites where soil characteristics are similar. It is important, also, to work out means of using information obtained from these control sites in evaluating permeability of soil profiles with different characteristics.

Realizing the immediate need for investigations of this kind, the Soil Conservation Service began a systematic study in the spring of 1947 to study soil profiles at sites where permeability measurements have been made; correlate the soil characteristics or clues with the seven permeability classes already tentatively established; and test the reliability of these clues for evaluating and predicting permeability rates. The seven permeability classes and the corresponding percolation rates as measured by the standard procedure are as follows:

1. Very slow—less than 0.05 inch per hour;
2. Slow—0.05 to 0.2 inch per hour;
3. Moderately slow—0.2 to 0.8 inch per hour;
4. Moderate—0.8 to 2.5 inches per hour;
5. Moderately rapid—2.5 to 5.0 inches per hour;
6. Rapid—5.0 to 10.0 inches per hour;
7. Very rapid—10.0 or more inches per hour.

#### RESULTS OF INVESTIGATIONS

Studies were made in the eight North Central states in 1947 and in the seven Southeastern states in 1948. At each site certain soil characteristics of each

<sup>1</sup> Uhland, R. E. Procedure for taking core samples. Mimeographed by Soil Conservation Service, October 2, 1947.

significantly different horizon between the depths of 6 and 54 inches were carefully examined and recorded. These characteristics include texture, structure, ease and direction of natural fracture when lumps are broken, size and number of visible pores, and intensity of mottling. The investigations show very interesting trends that should do much to coordinate and improve permeability determinations. But before these trends are considered in detail, it seems desirable to discuss briefly the way in which structure types were examined and some of the more significant variations in the over-all dimensions of the structural aggregates in the soils studied.

It was found that every horizon must first be appraised in terms of type of structure, that is, whether it is dominantly prismatic, cubical blocky, fragmental (irregular angular blocky), nuciform, or platy. But type of structure was not sufficient. More precise over-all information was needed on the relationship between the length of horizontal and of vertical axes; the amount and direction (whether horizontal, oblique, or vertical) in which the structural aggregates overlap, shingle fashion, one with another; and grade, or durability, of the aggregates.

For instance, when fragmental aggregates have horizontal axes three to four times longer than the vertical and a horizontal overlap of 40 to 50 per cent, the permeability is usually either very slow or slow, depending on whether there are any visible fine pores. On the other hand, if the length of the horizontal and vertical axes of the structural aggregates are more nearly equal and the horizontal overlap is less than 25 per cent, the permeability is likely to be no less than moderately slow even if the texture is heavy. This is also true for nuciform structure, since invariably the permeability is greater if vertical axes are longer than horizontal. Prismatic structure of strong grade is usually associated with very slow and slow permeabilities as in the subsoil of Clermont silt loam of Ohio. Prismatic horizons, however, may have moderately rapid permeability, as in Memphis silt loam. Here the prisms are porous and of weak grade.

A review of the data from detailed examination of 96 soil horizons on which permeability measurements are available shows some interesting trends. Data from all the observations made are reported in table 1. As might be expected, there are variations from the dominant trends within each permeability class. But these variations usually can be explained as results of the compensating influence of one or more of the recorded clues.

Seven horizons having measured percolation rates ranging from 0.01 to 0.04 inch per hour were examined. These are in the very slowly permeable class. All have a silty clay texture and are dense with no visible pores. Five of the seven have massive structure. In contrast to this are two horizons with a structure that is fragmental, in which the fragments have much longer horizontal axes than vertical and a horizontal overlap of 50 per cent. This structure apparently slows the downward movement of water in much the same manner as massive structure.

Eight horizons having slow permeabilities were examined. Seven of these had heavy to moderately heavy textures and moderately to very strongly durable

TABLE 1  
Relationship between measured percolation rates and soil characteristics

PERMEABILITY CLASS	RANGE OF MEASURED PERCOLATION RATES	NUMBER OF HORIZONS	TEXTURE	STRUCTURE				DIRECTION OF EASIEST NATURAL FRACTURE	SIZE OF SOILS AND NATURAL PORES	MOTTLING	REMARKS
				Type	Grade	Relation of horizontal and vertical axes	Overlap				
1. Very slow	in./hr. 0.01-0.04	$\begin{Bmatrix} 5 \\ 2 \end{Bmatrix}$	Heavy Heavy	Massive Fragmental	— V. strong	— Hor. > vert.	— 50% hor.	Horizontal Horizontal	None None	Strong Strong	— —
2. Slow	0.06-0.20	$\begin{Bmatrix} 7 \\ 8 \end{Bmatrix}$	Hvy-mod. hvy Mod. hvy	Fragmental Fragmental	Mod.-v. stg Moderate	Hor. > vert. Hor. > vert.	25-50% hor. 0-25% hor.	Horizontal Sigt oblique	Fine Medium	Mod. stg Moderate	— slightly cemented
3. Moderately slow	0.30-0.79	$\begin{Bmatrix} 12 \\ 19 \end{Bmatrix}$	Mod. hvy- hvy Heavy Heavy Medium	Fragmental Cubical blocky Platy Fragmental	Mod.-mod. stg Weak Weak-mod. Moderate	Hor. > vert. eq Equal Hor. > vert. Hor. > vert.	0-25% hor. 0-25% hor. 0-25% hor. 0-25% hor.	Sigt oblique Sigt oblique Horizontal Oblique	Fine-med. Fine Fine Fine	Strong Slight Moderate Moderate	— — — Mod. cemented
4. Moderate	0.90-2.18	$\begin{Bmatrix} 7 \\ 12 \end{Bmatrix}$	Mod.hvy- hvy Med.-mod.- hvy	Fragmental Nuciform	Strong-v. stg Weak	Eq.-hor. > vert. Equal	Sigt. oblique Oblique	Oblique Oblique	Med.-fine Med.-fine	Strong Slight	— —
5. Moderately rapid	2.58-4.73	$\begin{Bmatrix} 7 \\ 11 \end{Bmatrix}$	Med-hvy. Mod.hvy- hvy Mod.hvy	Nuciform Fragmental Cubical blocky	Mod-stg Moderate Moderate	Eq.-vert. > hor. Vert. > hor.- hor. > vert. Equal	Oblique Oblique Oblique Oblique	Vert.& obliq. Vert. & obliq. Vert. & obliq.	Med.-coarse Fine-coarse Fine	None-sigt Strong Strong	— — —
6. Rapid	5.12-9.77	$\begin{Bmatrix} 5 \\ 12 \\ 3 \\ 4 \end{Bmatrix}$	Mod.lt-hvy Mod-hvy Lt.-mod. lt	Nuciform Fragmental Single grain	Weak-mod. stg. Moderate	Eq.-vert. > hor. Vert. > hor. —	Oblique Oblique —	Vertical Vertical Vertical	Coarse-med. Coarse-med. Medium	None-mod. None-sigt —	— Smaller sand grains than 7.
7. Very rapid	10.15-100+	$\begin{Bmatrix} 21 \\ 27 \\ 3 \end{Bmatrix}$	V. lt.-mod. lt Mod. lt.- mod. hvy Mod. hvy-	Single grain Nuciform Fragmental	— Weak-mod. Weak-mod.	— Vert. > hor. Vert. > hor.	— Oblique Oblique	— Vertical Vertical	Coarse Coarse-med. Coarse-med.	None-sigt None-sigt —	Larger sand grains than 6.



fragmental structure with horizontal axes much longer than vertical and with 25 to 50 per cent horizontal overlap. In contrast to the two horizons with fragmental structure in the very slow class, all seven of these horizons had visible fine pores. Apparently the slight porosity accounts for the measured percolation rates of 0.06 to 0.20 inch per hour. The eighth slowly permeable horizon fractured most easily along slightly oblique rather than horizontal lines but remains in this class because of the compensating effect of a slight amount of cementation or induration.

Nineteen horizons of moderately slow permeability were examined. Their most conspicuous difference from the horizons in the slow class is that the 12 with fragmental structure and heavy or moderately heavy texture had less than 25 per cent horizontal overlap instead of 25 to 50 per cent. Also, lumps broke most easily along slightly oblique lines, and the visible pores were slightly larger than in the slowly permeable class. The five horizons with heavy texture and platy structure seem to have retarded downward water movement in much the same manner as those with fragmental structure where the degree of horizontal overlap and porosity were the same. Another clue brought out in this class is that a moderate amount of cementation may give a slower permeability than that indicated by texture. One horizon, except for its moderate cementation and medium texture, had characteristics similar to the 12 with heavy or moderately heavy textures.

Texture alone is not sufficient evidence for separating the moderately permeable from the moderately slowly permeable horizons, as textures for the 12 and 19 horizons in each class range from medium to heavy. Neither is type of structure sufficient. Other characteristics such as dimension and arrangement of structural aggregates, direction of easiest fracture, and porosity are the determining factors. For instance, seven of the 12 moderately permeable horizons were identical with 12 of the 19 moderately slow horizons in texture and type of structure. The significant difference seems to be the direction of overlap. It is along slightly oblique lines for the moderately permeable horizons and horizontal for the moderately slowly permeable horizons. The natural fracture for the moderate class is also oblique rather than slightly oblique, and the aggregates are slightly more durable. It is interesting to note also that five of the 12 horizons examined have weakly developed nuciform structure. But in every case the percolation rates for these horizons are in the upper range of the class, 1.78 to 2.18 inches per hour.

The 11 horizons with measured percolation rates of 2.58 to 4.73 inches per hour (moderately rapid class) show a wide range of textures—very fine sandy loams to silty clays. Seven of the 11 have nuciform structure, three fragmental, and one cubical blocky. The seven horizons with nuciform structure differ from the five horizons of the moderately permeable class with similar structure chiefly in having slightly longer vertical than horizontal axes, visible pores that range from medium to coarse instead of medium to fine, and easiest natural fracture along vertical and oblique lines rather than oblique alone. Similar differences—the relationship between length of horizontal and vertical axes, overlap, and

direction of easiest fracture—are significant in separating the three horizons with fragmental structure of this moderately rapid class from the seven horizons of the moderate class that have similar structure. The horizons with cubical blocky structure for the moderately rapid and moderately slow classes differ chiefly in that the former shows oblique overlap and the latter less than 25 per cent horizontal overlap.

Textures of the rapidly permeable horizons are, in general, lighter than those of the moderately rapid class but still show a wide variation, ranging from loamy fine sands to silty clays. Structure also shows a wide range: five nuciform, three fragmental, and four single grain. The significant clues for separating rapidly from moderately rapidly permeable horizons seem to be the relationship between vertical and horizontal axes and direction of easiest natural fracture. Without exception, permeability is greater whenever the vertical axes are longer than the horizontal and whenever the easiest natural fracture is in the vertical direction.

Twenty-seven horizons with very rapid permeability, percolation rates ranging from 10.15 to more than 100 inches per hour, were examined. Textures, in the main, are lighter than those of rapidly permeable horizons but still show a wide range extending from sands to very fine sandy clays. Type of structure seems to have significance, as 21 of the 27 horizons are single grain. Apparently larger particle sizes and the greater number and larger size of visible pores are of greatest significance when separating the horizons of this permeability rate from those with rapid rates.

Recent investigations on a limited number of deep sands show some promising trends. It was possible to separate the horizons with measured permeability rates of more than 10 inches per hour into three broad categories on the basis of observable characteristics. These are somewhat different from those described above. They include texture, presence of separates other than the dominant size that is responsible for texture, visible interstitial spaces, arrangement of sand grains around voids, and density of faces after lumps are broken.

#### CONCLUSIONS

In general, it would seem that structure is the most significant factor in evaluating permeability. But permeability cannot be correctly evaluated on the basis of type of structure alone. Other characteristics of the structural aggregates and their relation to one another must be considered. Examples are the relationship between length of the horizontal and the vertical axes, and the direction and amount of overlap of the aggregates. In some sections, heavy textures go along with slow permeability, and light textures with rapid permeability. But, in the main, texture alone is not a reliable clue. Nor is mottling, unless the reason for it is known. A soil may be mottled, regardless of its permeability, if the water is held by a barrier or is the result of seepage or perched water table. In some soils, the durability of structural aggregates seems to be correlated with permeability; in others, the size and number of visible pores, or the direction of easiest natural fracture. Usually, all the factors mentioned here

must be considered singly and in relation with one another. Permeability cannot be evaluated on the basis of one characteristic alone.

Observations of soil structure, direction of easiest natural fracture, and size and number of visible pores can be made in the field at the time samples are taken for permeability measurements. The experience gained by checking observable characteristics against measurements can be applied in evaluating the permeability of soils in much the same manner as a limited number of mechanical soil analyses serve to help identify the textural classification of all soils.

The study permitted a test of the usefulness of permeability clues. The author estimated the permeability class of 38 of the soil horizons reported in table 1 without previous knowledge of the measured percolation rates. The estimates were correct for 36 of the 38 horizons. One estimate was off by one class and the other (for a loamy fine sand) was off by two classes. It was found, however, that a strict adherence to clues that could be observed was necessary. Preconceived ideas not checked against measured data invariably caused trouble.

The investigations in the North Central and Southeastern states have been very useful not only in providing means for more correctly evaluating permeability but also in making those who participated more conscious of the significance of soil properties in conservation farm planning. The results indicate that more data are needed before definite conclusions can be shown. It is hoped, however, that this preliminary study will stimulate similar work in other parts of the country.



# GLINKA'S LATER IDEAS ON SOIL CLASSIFICATION

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Few men in the history of scientific agriculture have attained greater recognition than Glinka. According to Kellogg (5, p. 344):

The translation of Professor Glinka's lectures . . . made available in western Europe and the United States especially, new facts and ideas developed by the great Russian school of soil science of which Professor Glinka was the distinguished leader for many years. The book had a tremendous influence upon the whole course of soil science, and especially of soil classification and geography in the United States. . . .

It is seldom recognized, however, that soil scientists outside of Russia were presented with Glinka's earlier ideas after he himself had reviewed them materially. The first edition of his book on soil classification in Russian appeared in 1908 (1). In 1914 this book was translated into German by H. Stremme (2). In 1927 part of the German edition of 1914 was translated into English by C. F. Marbut (3). Meanwhile, the original volume had undergone two successive revisions (1915 and 1926). Then, in 1931, the last, a posthumous volume (4), was published. It comprises 612 pages, nearly twice the 365 pages in the German edition, and four times the 150 pages in the English edition.

The profound discrepancy between the original and the last editions of Glinka's book is obvious from the following statement of the author in the latter (4, p. 313): "I consider it necessary to point out that a general outline of the new soil classification proposed by me was published in 1921, and later in 1922, 1924, and 1925. Therefore, it appears incomprehensible to me that, not only west European, but even Russian pedologists continue to quote my old classification of 1915. . . ." Strangely enough, Glinka's objections to out-dated quotations from the earlier edition are still being constantly overlooked. For example, works on soils and related subjects published in the English language during the last decade still, with rare exceptions, quote the translation of the original text of 1908.

In the last edition, Glinka suggested the following classification of soil-forming processes and resulting products:

## *I. Lateritic Type*

1. Typical laterites; 2. Red earths of subtropical latitudes; 3. Red earths and yellow earths of warm regions of temperate latitudes.

## *II. Podzolic Type*

1. Brown earth (as understood by Ramann); transitional variety to lateritic type; 2. Glei-podzolic soils; transition to bog type; 3. Peat-podzolic soils; 4. Primary latent podzols of forests; 5. Primary podzolic soils; 6. Meadow-podzolic soils; 7. Chernozem-like soils forming transition from meadow-podzolic soils to chernozems; 8. Secondary podzolic

soils including degraded chernozems, a transitional variety from degraded forest soils to chernozems.

### III. *Steppe Type*

1. Chernozems and related types; 2. Chestnut soils; 3. Brown soils; 4. Sierozems;
5. Red colored soils of subtropical desert-like prairies.

### IV. *Bog Type*

- A. *Bog soils proper*: 1. Meadow-swamp soils; 2. Soils of alkali swamps and marshes.
- B. *Solonchak soils*: 1. Solonchaks; 2. Solonchak-like soils.

### V. *Solonetz Type*

1. Leached solonetz soils; 2. Solonetz soils; 3. Solonetz-like soils.

Glinka pointed out that this scheme of classification does not cover all varieties of soils which may be found in nature, but outlines the most important groups.

Thus, Glinka considerably simplified his earlier classification and entirely abandoned his original scheme based on development of soils under optimum, average, insufficient, excessive, and temporarily excessive moisture. Obviously, at the later date, he realized the full importance of the temperature factor stressed by Ramann. Moreover, Glinka discarded the concepts of endodynamomorphic and ectodynamomorphic soils. In his last edition he mentioned these terms only incidentally and rather apologetically. The following statement (4, p. 314) may throw some light on his attitude:

Endodynamomorphic (or better to say *endodynamogenic*) soils appear to be temporary phenomena which exist as long as the chemical composition of the parent material is unchanged. After parent material is modified in its chemical composition, endodynamogenic soils develop into soils characteristic of the zone of their occurrence; thus, rendzinas in a podzol zone are transformed in time into podzolic soils.

Though Glinka recognized the general soundness of the soil classification proposed by Sibirtzev, he found the concepts of intrazonal and azonal soils to be artificial and superfluous. In support of his opinion he cited a number of soil types that may be classified as zonal, intrazonal, or azonal (podzolized soils within the region of chernozem, solonetz soils of river valleys, etc.). Although Glinka did not state this specifically, he seemed to favor two basic concepts of soil: mature or genetically developed soils, and immature or embryonic soils. The latter he regarded as "geological deposits" rather than "soils," and mentioned them only in passing.

It is obvious that Glinka did not consider the "brown earth" of Ramann an independent type. He stated (4, p. 313) that soils classified under this name in western Europe actually "represent a conglomerate group; this group includes among its many varieties weakly podzolized soils which lost their podzolic horizon by plowing, and also tertiary red earths which were modified by present conditions."

Glinka's ideas on the classification of tropical soils are expressed in the following quotation:

It is possible that in tropical regions additional varieties of the already established types will be found. In spite of the fact that in recent years there have appeared many new publications dealing with tropical soils (Moore, Stremme, Walter, Wiegner, Blanck, Heilman, Lang, Lacroix, Harrassowitz, and Van Baren), we still know very little about these soils. Therefore, we have little justification for speaking about new types of soil development. Apparently in tropical regions, aside from laterites and red earths, which are common exclusively to the tropics, there occur also podzolic soils and brown earths, soils of steppe type, solonetz, solonchak, and bog soils. However, there is a dearth of knowledge on the distribution of soil types within the tropical soil zones and the relation of soils to topography.

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## BOOKS

*Atomic Energy Development.* By UNITED STATES ATOMIC ENERGY COMMISSION, 1947-48. Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. Pp. 213. Price, paper-bound, \$0.45.

Atomic energy development is now 10 years old, and the monograph is designed to present as complete a picture as is permissible of the present state of the work under way. Full-page plates show the various plants that are in operation and the community centers associated therewith. The several parts of the report deal with production, application, research in the physical sciences and in biology and medicine, information service, security, finance, organization and personnel, and patents and inventions. In the discussion on biology, under the heading: "Does radiation stimulate plant growth?" is a report of tests carried out in 14 states on 19 crops which "indicate strongly that the farmer cannot expect increased yield from money invested in radioactive materials available at present."

*The Chemistry and Technology of Enzymes.* By HENRY TAUBER. John Wiley & Sons, Inc., New York, 1949. Pp. 550, figs. 56. Price \$7.50.

This is an extension of the author's *Enzyme Technology*, which was published in 1943. In the present volume, the first 265 pages deal with the chemistry of enzymes, and are entirely new. The remainder of the book is concerned with the technological phases of the subject, and has been extensively revised. The author reviews the work of some 1,700 research specialists in this field, a long list of references being appended to each of the 32 chapters. The book is well written and illustrated and gives a very good over-all picture of the subject. Though the developments in enzyme chemistry and technology have been so rapid that it was impossible for the author to cover all phases of the subject equally well, this is a highly important and useful book that merits a place on the shelf of every specialist in enzymology.

*Drug Plants of Africa.* By THOMAS S. GITHENS. University of Pennsylvania Press, Philadelphia, 1949. Pp. 125. Price, paper-bound, \$2.25.

This is number 8 of a series of African handbooks published under the direction of the Committee on African Studies of the University of Pennsylvania. The author has undertaken to collate and synthesize the vast store of empirical information developed by the inhabitants of the entire continent of Africa on a great variety of plants being used for medicinal purposes. The text deals with the chemical basis for the use of these drug plants, and the actual use that is being made of them. The remaining two thirds of the book is made up of tables showing plant drugs exported from Africa into the United States and England, generic synonyms, definitions of medical terms, chemical basis of drug action, and specific utilization of drug plants. A selected bibliography of 57 titles is appended.

The book could well be of considerable value to plant scientists who are interested in developing new plants for agricultural production or in studying the quality of plants already in production in this country. It would appear that the African natives have a natural cure for almost every ill.

*Pioneers of Fertility.* By CRICHTON PORTEOUS. Fertilizer Journal, Ltd., London, 1949. Pp. 125, illustrated by Michael Ayrton. Price 10/-.

The author begins his book with a look into the far distant past, where he picks up the beginning threads of the search for the secrets of soil-plant relationships. These lead through the lives and works of Fitzherbert of Norbury (1523), Walter Bligh (1652), Jethro Tull (1674-1741), Arthur Young (1741-1820), Humphrey Davy (1778-1829), John Bennett Lawes (1814-1900), Augustus Voelcker (1822-1884), and Robert Warington (1837-1907), with a number of others interspersed. The final chapter deals with "the amazing future." The book makes interesting reading. Unfortunately, it needs extensive development to be of any great value to those who would like to know more about the interesting details of the lives of these highly important personalities.

*Plant Nutrient Deficiencies.* By R. L. COOK AND C. E. MILLER. Special Bulletin 353, Michigan Agr. Exp. Station, East Lansing, 1949. Pp. 80, figs. 64. Price \$1.

This highly interesting and attractive bulletin deals with plant-nutrient deficiencies as diagnosed by plant symptoms, tissue tests, and soil tests. It contains 16 pages of photographs in color, showing nutrient-deficiency symptoms on a wide range of plants. The Purdue method of tissue testing and the Spurway method of soil testing are recommended. The purpose of the bulletin is to place in the hands of agricultural workers both illustrative materials and methods that will enable them to make correct diagnoses of deficiencies. The bulletin has a ring binding, which suggests that possibly replacements might be sent out from time to time for some of the leaves. It has a hard-board cover, and lies flat on being opened. It should prove highly useful, not only in Michigan but elsewhere.

*Practical Spectroscopy.* By GEORGE R. HARRISON RICHARD C. LORD, AND JOHN R. LOOFBOUROW. Prentice-Hall, Inc., New York, 1948. Pp. 605. Price \$5.

Interest in spectroscopy is such that this book should enjoy wide reading and study. The authors are associated with the spectroscopy laboratory of the Massachusetts Institute of Technology, and represent the fields of physics, chemistry, and biophysics, respectively. They bring wide knowledge and experience to bear on the use of spectroscopy as a research tool. The several chapters deal with the spectrum, techniques, selection of instruments, spectroscopes and spectrographs, care and adjustment of instruments, illumination, photography, light sources, identification of spectrum lines, origins of atomic spectra, molecular spectra, spectral intensity measurements, photographic

photometry, absorption spectrophotometry, qualitative spectrographic analysis, quantitative spectrochemical analysis, infrared region, Raman spectroscopy, the vacuum ultraviolet, and interferometric spectroscopy. The book is exceptionally well illustrated and contains a great variety of very useful information for the man who is contemplating the purchase of instruments or who, already having them, needs to know more about how to operate them. In writing this book, the authors have rendered a highly important service to scientists.

*Radioisotopes in Nutritional Trace Element Studies.* By C. L. COMAR. McGraw-Hill Publishing Company, Inc., New York, 1948. Pp. 44.

Three papers that were published in *Nucleonics* have been printed and made available in this small paper-bound brochure. These papers give an excellent review of the work in this field and in such detail as to make the discussion of great value to research workers. A list of 121 references is given. The author has rendered an exceptionally valuable service in the preparation of these papers.

*Runoff Water as an Agent in the Loss of Soluble Materials from Certain Soils.* By JAY C. BRYANT AND C. S. SLATER. Iowa State College Journal of Science, vol. 22, pp. 269-312, 1948.

This is a detailed report of losses of soil, water, and soluble constituents from Ontario and Dunkirk soils during a 13-month period, with total losses and average concentrations for 16 runoffs during one year. The conclusion is reached that "although losses of solutes reported in runoff are small, an analysis of the factors that produce variability in runoff losses indicates that appreciable losses may be incurred under less favorable conditions." A bibliography of 31 papers is appended.

*Soil Fertility.* By I. DE V. MALHERBE. Oxford University Press, New York, 1948. Pp. 296, plates 9, figs. 21. Price \$6.50.

The author of this book is professor of agricultural chemistry in the University of Stellenbosch, in South Africa. The book is an English version of the revised sixth Afrikaans edition. The three parts of the book deal with the nutrition of plants, soil science, and fertilizers and manures, their preparation, properties and use. The book is intended for use in agricultural high schools, by prospective young farmers, and, possibly to a lesser extent, by university students. No references or supplemental reading lists are given. It is of special interest to note that important increases in crop yields for manganese, copper, zinc, and boron are reported with supporting data. The book would be of general interest to all soil-plant scientists.

*Types de Sol de l'Afrique du Nord.* By EMILE H. DEL VILLAR, Institute Agricole D'Algerie, Tunis-Rabat, 1947. Pp. 152. Price 594 frs.

This is part 2 of a treatise on the soils of the world. It contains a few pages of additions and corrections to part 1. Part 2 includes chapter 4, which gives descriptions of the profiles of siallitic soils, and chapter 5, which deals with their

geographic distribution. The author is president of the Sous-Commission Méditerranéenne of the International Society of Soil Science and is on a mission at l'Institut Scientifique Chérifien de Rabat.

*Vegetable Growing.* Fourth Edition. By JAMES E. KNOTT. Lea and Febiger, Philadelphia, 1949. Pp. 314, figs. 81. Price \$4.

Some 70 vegetables, from artichokes to yams, are discussed in this very well written book. A great deal of practical information is required to cover the subject around which the book is written. Changes being made in the techniques of vegetable growing are so rapid that frequent revisions have been necessary to keep this book up to date. The material is divided into 29 chapters, which cover factors affecting plant growth; plant-growing equipment; seed and seedage; managing and fertilizing soils; weed, disease, and insect control; storage; and, finally, the several groups of crops. A list of suggested readings is appended to each chapter. The illustrations are well chosen. The book is intended for classroom purposes, but every vegetable grower will find in it material of considerable interest and value. The cover, showing a vegetable field scene in color, is especially attractive.

THE EDITORS.

# EFFECT OF EXCHANGE CAPACITY OF CLAY MINERAL AND ACIDOID CONTENT OF PLANT ON UPTAKE OF SODIUM AND CALCIUM BY EXCISED BARLEY AND PEA ROOTS

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Application of the results of ion uptake by plants, obtained by the regular solution-culture technique, to the nutrition of plants in soils and in clay-suspension cultures discloses certain discrepancies and encounters serious difficulties. The presence of colloidal particles in such systems introduces a change in the properties of ions. The activities of adsorbed ions are quite different from those in solution. Since the activity is an expression of the effective concentration, and since the divergence between the activity and the concentration is more pronounced for adsorbed ions than for free ions, one must, when dealing with colloids, work with activities rather than with concentrations, in spite of the fact that the exact quantitative relationship between concentration and activity in the colloidal phase is still unknown. The fact that different clays have varying exchange capacities is an indication that they possess micellar solutions of different ionic activities.

According to the law of mass action, as expressed in the Donnan theory of membrane equilibria, the distribution of ions of different valence in a Donnan system is governed by the relative activity of both inside and outside solutions. The distribution of monovalent and divalent cations between the colloid and the outside solution is generally given by the following equation:

$$\frac{(M^+)_i}{(M^+)_o} = \frac{\sqrt{(M^{++})_i}}{\sqrt{(M^{++})_o}},$$

where  $(M^+)_i$  and  $(M^+)_o$  represent the activity in the inside and outside solutions respectively of the ion  $M^+$ .

From the square root relationship, it follows that divalent ions will accumulate to a greater degree than monovalent ones in the phase with the higher activity. Furthermore, it follows that a relatively concentrated inside solution and a dilute outside solution would favor the adsorption of divalent ions. Accordingly, other things being equal, the higher the exchange capacity of the material, the higher will be the ratio of divalent/monovalent exchangeable ions. Conversely, among materials having different exchange capacities and containing adsorbed monovalent and divalent ions in equivalent amounts and similar ratios, the one with the higher exchange capacity will release its monovalent

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ions relatively more readily and its divalent ions less readily to the outside solution than the one with the lower capacity. A detailed discussion of this subject has been published in a series of papers by Mattson and co-workers (4, 6, 7, 8).

If the plant-soil system is regarded as a Donnan system consisting of two colloidal phases, the relative distribution of cations of different valence between the two phases will depend upon the exchange capacity of both plant and clay mineral. Accordingly, other things being equal, the same plant is expected to take up larger proportions of the monovalent cations and smaller proportions of the divalent cations, the higher the exchange capacity of the clay mineral. Also, if two clay minerals having different exchange capacities are mixed in varying proportions, the Ca/Na ratio in the plant will increase with an increase in the percentage of the clay mineral having the lower capacity. On the other hand, the relative distribution of cations in different plant species having varying acidoid contents will depend on the activity of the absorbing roots. The Donnan distribution of ions of different valence will tend to be reflected in the composition of the plants.

The present paper deals with a study of the following points: (a) uptake of sodium and calcium by excised barley roots from Na-Ca-kaolin suspensions in comparison with uptake from Na-Ca-bentonite suspensions; (b) uptake of sodium and calcium by excised pea roots from mixtures of Na-Ca-bentonite-kaolin suspensions having the same (Na + Ca) ions but varying proportions of kaolin and bentonite; (c) uptake of sodium and calcium, from Na-Ca-bentonite suspensions, by excised barley roots in comparison with pea roots.

#### METHOD OF EXPERIMENTATION

Barley and pea plants were grown in a dilute Hoagland solution by a modified technique developed originally by Hoagland and Broyer (2). About one eighth of the regular concentration, with ferric tartrate as a source of iron, was used. The barley plants were grown for 3 weeks, during which the solution was changed once after 12 days, and the pea plants were grown for 2 weeks after transplantation, during which time the solution was changed once after 8 days. The plants were aerated from an oxygen tank during their last week of growth. After the given time, the roots were excised. The plants grown according to this technique are characterized by their low salt and high sugar contents, and thus have a higher capacity to accumulate ions over the short period of the experiment.

The excised roots of each plant species were mixed together, washed with distilled water, and slightly centrifuged. About 18 gm. of barley roots and 32 gm. of pea roots were placed in Na-Ca-suspensions prepared in the following manner: Portions of H-bentonite and H-kaolin having a cation-exchange capacity of about 90.0 and 3.0 m.e. per 100 gm. respectively were titrated up to pH 5 to 6 with NaOH and  $\text{Ca}(\text{OH})_2$ , respectively to give a total of 5.0 m.e. of Na and Ca in the proportions shown in tables 1, 2, and 3. The suspensions were made to volumes of 2 liters with distilled water. The roots were left in the clay suspensions for about 10 hours. During this time the suspensions were continuously aerated

and frequently stirred. After the absorption time, the roots were removed from the suspensions, washed with distilled water, dried at 105°C. for 24 hours, weighed, and ashed at about 500°C. The ashes were dissolved in HCl, and the silica was separated. Sodium was determined as sodium magnesium uranyl acetate after separation of phosphate. Calcium was determined as oxalate and titrated with permanganate. The results are shown in tables 1, 2, and 3.

#### EXPERIMENTAL RESULTS AND DISCUSSION

##### *Ion uptake by same plant from materials of different exchange capacities*

In studying nutrient absorption by the same plant from materials having different exchange capacities, we could assume the composition of the surface layer of the absorbing roots to be constant over the short period of the experiments and the difference in ion uptake could be attributed mainly to the influence of the medium. The results of such a study are shown in table 1.

TABLE 1  
*Uptake of Na and Ca by excised barley roots from Na-Ca-kaolin and Na-Ca-bentonite suspensions*

SYSTEM	CATIONS ON CLAY		CATION CONTENT OF OVEN-DRIED ROOTS		Ca/Na IN ROOTS
	Na	Ca	Na	Ca	
	m.e.	m.e.	m.e.*	m.e.*	
Na-Ca-kaolin . . . . .	0.5	4.5	13.59	9.74	0.72
	2.5	2.5	20.60	9.45	0.46
	4.5	0.5	25.01	8.50	0.34
	0.5	4.5	28.39	12.75	0.45
Na-Ca-bentonite . . . . .	2.5	2.5	29.93	11.06	0.37
	4.5	0.5	39.46	9.47	0.24

\* Per 100 gm.

The uptake of both sodium and calcium from the two clays has to be considered from two different points of view.

First, comparison of the absolute values of sodium and calcium taken up by barley roots shows that at equal concentrations and ratios of the two adsorbed ions, the plants take up more sodium and calcium from bentonite than from kaolin suspensions, as shown in table 1. These results are in conformity with those previously obtained by one of the authors for homoionic potassium and zinc clays and show the effect of the type of clay mineral on the uptake of ions (1). As an explanation of this, it was reported "that both the carbonic acid theory and the soil solution concept of plant nutrition cannot explain the results and that some additional factor not yet fully evaluated, but somewhat associated with the nature of the colloidal clay must come into play".

Second, comparison of the relative uptake of the two ions as indicated by Ca/Na in roots (table 1) shows that relatively more calcium and less sodium is taken up from kaolin than from bentonite suspensions. This means that kaolin holds more firmly to its sodium and less firmly to its calcium than does bentonite.

Similar results were obtained by Mattson (7) for potassium and calcium. The clay mineral with the higher exchange capacity, higher activity, released its monovalent ions to the plants more readily and its divalent ions less readily than the clay mineral with the lower exchange capacity. Accordingly, bentonite, which has a higher exchange capacity, will supply the plant relatively better with its sodium ions, whereas kaolin, with a lower capacity, will supply the plant relatively better with calcium. Although the exact quantitative relationship between concentration and activity in the colloidal phase of a Donnan system is still unknown, the valence effect reveals itself as shown by Ca/Na in the roots. This distribution is governed by the relative activity of the inside and outside solutions.

It makes no difference which theory or combination of theories is responsible for ion uptake by plants in soils and clay suspensions. Whether the mechanism of cation uptake is considered to be through direct contact exchange between the double layers of the colloidal clay and root, as suggested by Jenny *et al.* (3) or through the soil solution, as believed by Hoagland and others, the valence

TABLE 2

*Ca/Na ratio in pea roots placed in bentonite-kaolin mixtures having 0.5 m.e. Na and 4.5 m.e. Ca but varying percentages of kaolin and bentonite*

SYSTEM	BENTONITE	KAOLIN	Ca/Na IN ROOTS
	<i>per cent</i>	<i>per cent</i>	
Na-Ca-bentonite-kaolin . . . . .	0	100	8.38
	25	75	8.12
	50	50	6.79
	75	25	6.83
	100	0	5.66

effect in relation to the ion activities of soil-plant Donnan system seems to come into play and to reveal itself in the plant composition.

*Ion uptake by excised pea roots from kaolin-bentonite mixtures*

If the relationship found between the relative uptake of calcium and sodium by excised barley roots and the exchange capacity of the clay material is true, the Ca/Na ratio must decrease in the roots when the percentage of the mineral having the higher capacity is increased in the mixture. This has been investigated by using pea roots and Na-Ca-kaolin-bentonite mixtures. All mixtures contain 0.5 m.e. of Na and 4.5 m.e. of Ca. The kaolin and bentonite percentages in the mixtures varied between 0 and 100.

The results, shown in table 2, are in accordance with what is to be expected if the uptake of ions of different valence by plants obeys the Donnan theory. They also confirm results obtained for the individual minerals.

It is evident that the Ca/Na ratio in the roots is governed by the percentage of the two minerals in the mixtures. A decrease in the contents of kaolin in the mixtures is accompanied by a decrease in the Ca/Na ratio in the roots. An increase in the contents of bentonite and a decrease in kaolin result in an increase in the activity of the clay system, and according to the theory, the release of



monovalent ions will be relatively favored, and the reverse for divalent ions. As a result of this, the Ca/Na ratio in the roots decreases.

*Ion uptake by different plants from same clay mineral*

Ion absorption by plants depends not only on the properties of the medium but also on the plant species, as the composition of the two surface layers is determined by both. The effects of the type of clay mineral on the relative uptake of sodium and calcium by excised barley roots have been discussed. Let us now investigate the reverse case, that is, the effects of plant species on the uptake of sodium and calcium from the same clay material. The experiments were performed with excised barley and pea roots, which were placed in bentonite suspensions having a total (Na + Ca) of 5.0 m.e., in the ratios given in table 3.

TABLE 3

*Uptake of Na and Ca from bentonite by different plant species (barley and pea roots)*

SYSTEM	CATIONS ON CLAY		CATION CONTENT OF OVEN-DRIED ROOTS		Ca/Na IN ROOTS
	Na	Ca	Na	Ca	
Barley roots					
Na-Ca-bentonite.....	m.e.	m.e.	m.e.*	m.e.*	
	0.5	4.5	28.39	12.75	0.45
	2.5	2.5	29.93	11.06	0.37
	4.5	0.5	39.46	9.47	0.24
Pea roots					
Na-Ca-bentonite.....	0.5	4.5	5.71	32.34	5.66
	2.5	2.5	8.26	26.69	3.23
	4.5	0.5	12.17	20.14	1.71

\* Per 100 gm.

From equal concentrations and ratios of sodium and calcium adsorbed on the same clay mineral, different plant species absorb the two ions in different amounts. It was found that barley roots take up more sodium and less calcium, whereas pea roots take up more calcium and less sodium, as shown in table 3. These results suggest that the two plant species must differ in their acidoid content or in the activity of the ions in their micellar solutions. Mattson *et al.* (5, 7) have found that different plants differ greatly in their acidoid contents. They found that the exchange capacity<sup>2</sup> of roots from 8-day-old pea plants is 71 and that of rye 29.5 m.e. per 100 gm. of air-dried matter. The corresponding value of 3-week-old barley roots amounted to 22.7 m.e. The exchange capacity of pea roots is therefore of about the same magnitude as that of bentonite. Since, at given outside concentrations of the ions, the relative distribution of monovalent and divalent ions is determined by the exchange capacity of the plant, the valence effect will tend to reveal itself in the composition of the plants. The greater the acidoid content of the plant, the greater will be the divalent/monovalent ratio

<sup>2</sup> Unpublished data.

in the plant. This explains the higher Ca/Na in the pea roots and the lower Ca/Na in the barley roots (table 3) and may offer a physicochemical explanation of the high calcium content of the legumes.

It is known that ion uptake by the same plant depends, among other things, upon the activity of the ions in the medium. Further, ion uptake by different plant species from the same mineral must depend upon the properties of the absorbing root. As a colloidal system, the plant root in contact with another colloidal system—clay mineral—results in a temporary equilibrium status between the plant and the colloidal medium in which the interaction between their two double layers is of importance. The result of this interaction is reflected in the composition of the plant. Other things being equal, the difference in plant composition will be mainly due to differences in the activities of the absorbing substances.

#### SUMMARY

The uptake of adsorbed sodium and calcium from kaolin and bentonite by excised barley roots was studied. From equal concentrations and ratios of the two ions, the roots remove more calcium and sodium from bentonite than from kaolin. When the relative uptake, as indicated by Ca/Na in roots, is compared, relatively more calcium and less sodium are removed from kaolin than from bentonite.

The uptake of sodium and calcium by excised pea roots from kaolin-bentonite mixtures having equal Na and Ca ions but varying percentages of the two clays, shows a decrease in the Ca/Na ratio in the roots with the increase in the bentonite content of the mixtures.

The effect of the acidoid content of plant on the uptake of sodium and calcium from bentonite suspensions was also studied. The results show a higher Ca/Na ratio in the pea roots with the higher acidoid content and a lower ratio in barley roots with the lower acidoid content.

These findings can be explained on the basis of the Donnan theory of membrane equilibria, as the results are in good qualitative agreement with those expected according to this theory.

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# THE FIBERGLAS ELECTRICAL SOIL-MOISTURE INSTRUMENT

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For years research workers have sought an instrument with which rapid and reliable soil-moisture measurements could be made in field and laboratory. Many types of instruments have been proposed or developed, the most promising being those which involve measurement of electrical resistance in a porous dielectric that is in moisture equilibrium with the soil enclosing it. In a 1946 paper (3) one of the authors listed the requirements which must be met by a satisfactory soil-moisture instrument, and described one incorporating two important improvements over earlier instruments of the resistance-measuring type. First, resistance was measured in the soil unit of this instrument within a fiberglass fabric which contained such a wide range of pore sizes that its moisture content responded to soil moistures from air-dryness to saturation. Second, the resistance was measured with an alternating-current ohmmeter which permitted instantaneous readings.

Since the appearance of that paper, the fiberglass instrument has been improved, and much has been learned about its operating characteristics. The instrument is being manufactured commercially, the soil and meter units having been obtainable since 1947 by agencies wishing to test them under their own conditions. In 1947, also, a manual (5) was prepared in which the instrument was described and instructions for its use were presented<sup>2</sup>.

The purpose of the present paper is to describe the fiberglass soil-moisture instrument as now designed and to present results of the more significant studies made with it since 1946. An instrument of similar design was recently described by Bouyoucos and Mick (2). Their soil unit also utilizes fiberglass (or nylon) fabric and is in several respects much like that described in the present paper. Their findings are encouraging to the writers because they corroborate much of what has been learned here in independent investigations.

## THE INSTRUMENT

The soil-moisture instrument consists of two parts: the soil unit and the meter unit. The soil unit is intended to be buried permanently at the point where moisture measurement is required. The meter unit is portable and is used to measure the electrical resistances of those elements of the soil unit with which soil moisture and temperature can be determined.

*The soil unit* (fig. 1) consists of a moisture-sensitive element and a thermally

<sup>1</sup> Forester and forestry aide, respectively, California Forest and Range Experiment Station, maintained by the Forest Service, U. S. Department of Agriculture, in cooperation with the University of California, Berkeley.

<sup>2</sup> This manual, and information regarding availability of the instrument, can be had, upon request, from the Director, California Forest and Range Experiment Station, P. O. Box 245, Berkeley 1, California.

sensitive element enclosed in a monel case. The moisture-sensitive element is a sandwich composed of two monel screen electrodes separated by two thicknesses of fibreglas cloth and wrapped around with three thicknesses of the same material. The electrical resistance between screens, through the fibreglas cloth, varies in response to changes in moisture content of the soil in which the unit rests. The thermally sensitive element is a model 7A thermistor manufactured by the Western Electric Company (1). This resistance thermometer is far superior to the wire-wound type used in earlier models of the soil unit. Its resistance at 77°F. (approximately 1,000 ohms) and its high temperature coefficient (ten times that of copper or platinum) make corrections for lead-wire resistance unnecessary, and increase the ease with which accurate temperature determinations can be made.

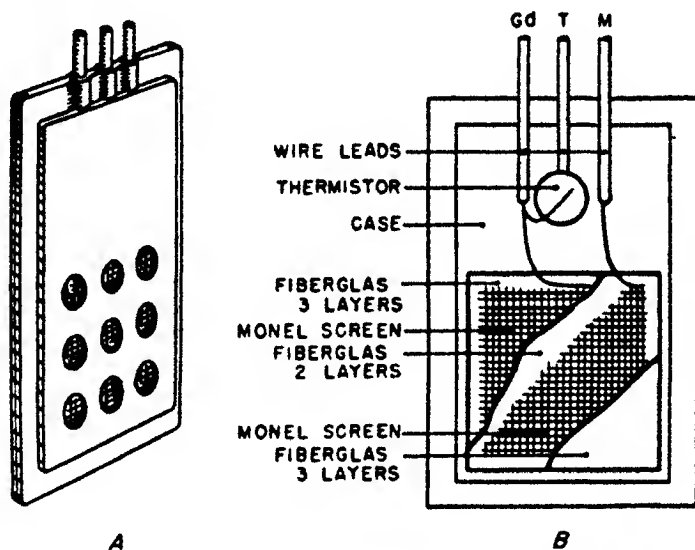


FIG. 1. THE SOIL UNIT OF THE SOIL-MOISTURE INSTRUMENT  
Outside dimensions of the case, 1 inch by  $1\frac{1}{2}$  inches by  $\frac{1}{2}$  inch

The monel case of the soil unit consists of two identical half-shells of 25-gage metal which are die-formed to ensure dimensional accuracy and rigidity. When assembled and spot-welded along the flange-edges, the case serves to compress the fibreglas uniformly, and good capillary contact between soil and fibreglas is ensured by the thinness of the metal.

The present design of the soil unit includes several improvements over the one previously described. The thinness ( $\frac{1}{2}$  inch) and rigidity of the unit make its installation in the soil easy. The metal case serves as an electrical shield to the fibreglas element, thus minimizing any tendency for electrical measuring currents to pass through the soil outside the unit. It also ensures good thermal contact between the soil and the fibreglas and thermal elements. The fibreglas now used is of a type made especially to withstand very high temperatures. Almost all impurities have been removed from the glass during manufacture, so that the

cloth is composed of nearly pure silica. As a result, its water-retentive properties are better than those of other fibreglas fabrics, and it is believed that the cloth is more resistant to deterioration upon exposure. Finally, the thinness of the fibreglas sandwich (0.072 inch) and its exposure to the soil on both sides minimize the time required for water in the fibreglas to reach moisture equilibrium with that in the soil. The fibreglas sandwich holds slightly less than 0.4 gm. of water when saturated. Because of this small quantity, no correction for water held in the sandwich is required during calibration tests in which 100 or more gm. of soil is used.

The meter unit is a battery-operated alternating-current ohmmeter (fig. 2), entirely self-contained within a case approximately 8 inches wide, 12 inches long, and 5 inches high. Alternating current of 90 cycles per second is generated by

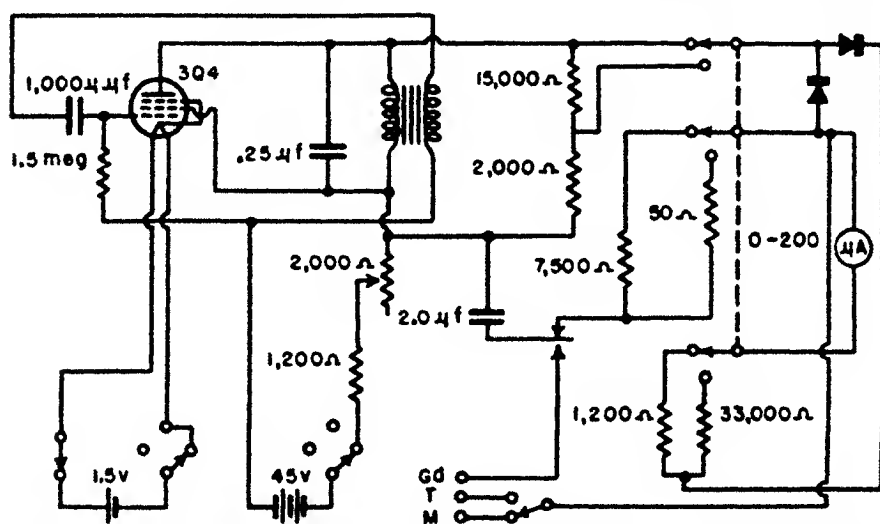


FIG. 2. CIRCUIT DIAGRAM OF THE METER UNIT, AN ALTERNATING CURRENT OHMMETER

the vacuum-tube oscillator and is fed into either the moisture- or the temperature-sensitive element of the soil unit. The emerging current is rectified so that its magnitude can be indicated directly on the microammeter. The calibration curve of the meter is such that, at low scale, sensitive measurements can be made in the range from 50 to 10,000 ohms; at high scale, the useful range is from 8,000 to about 3,000,000 ohms. This range has been sufficient to cover the soil-unit resistances in all soils so far studied, from pore-space saturation to moistures well below the wilting point, as will be shown later. Yet the meter is sufficiently sensitive to permit thermistor measurements with which temperature differences of about 1° F. can be detected between 10 and 110° F.

Soil and meter units built according to the designs set forth in figures 1 and 2 are being manufactured commercially. Dies have been prepared so that soil-unit cases can be made as nearly alike as possible, and assembly procedures have been devised to ensure the greatest possible uniformity in the completed units.

## RESULTS OF EXPLORATORY STUDIES

*Relation between temperature and resistance of the moisture element*

The resistance of the moisture-sensitive element varies with changes in temperature as well as in moisture content. For the most precise indication of moisture, therefore, the resistance measured must be converted to the resistance the element would have shown, under the same moisture conditions, at some

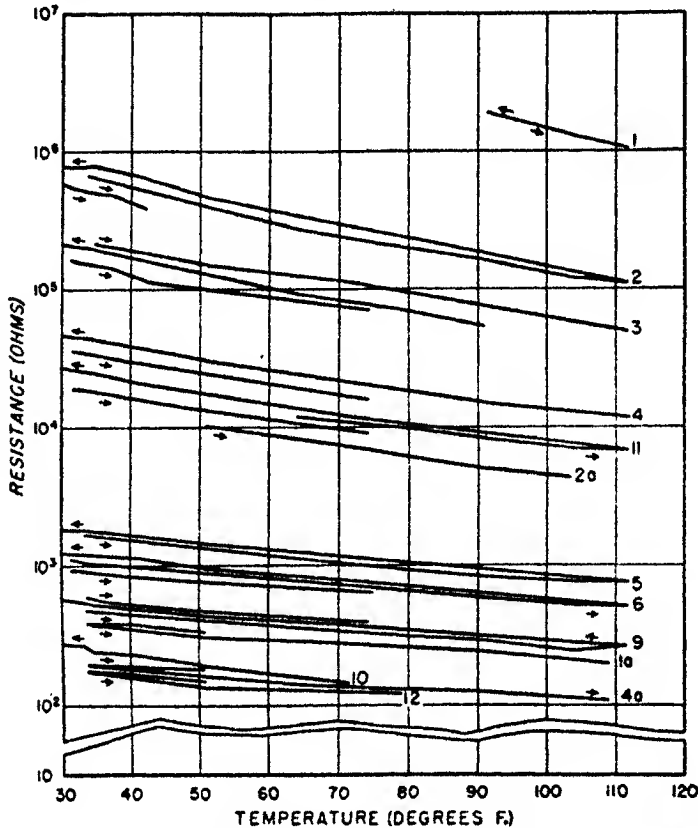


FIG. 3. TEMPERATURE RESPONSE OF SOIL UNITS PACKED IN SOIL BLOCKS HELD AT CONSTANT MOISTURE

Each numbered line represents a soil with a different moisture content. Arrows show direction of temperature change.

standard temperature. (In the soil studies made to date the standard temperature has been 60° F.) It will now be clear why the temperature-sensitive thermistor has been incorporated in the soil unit.

The temperature response of the moisture-sensitive element is shown in figure 3, which presents data upon which a standard temperature correction chart has been based. The several lines in the figure represent the resistance response of 13 soil units buried in 13 jars of soil, each maintained at a different moisture content and carried through a range of temperatures between 30° and 110° F.

The soils used included several samples each of Yolo silt loam, Yolo fine sandy loam, Altamont clay, and Hanford loamy sand.

No attempt has been made to designate the soil represented by each line, because analysis of the data showed that units in the several soils responded to temperature in exactly the same way. The slope of the temperature: resistance line is the same for these soils when, at a chosen temperature, they have the same resistance value. It will be fortunate if this relation is found to hold also for a wider variety of soils, for then a single temperature correction chart will find wider application. The present data indicate, at least for a wide textural range, that it is soil moisture, and not texture, that establishes the slope of each line.

All lines in the figure are essentially linear and show a gradual increase in slope as resistance at any temperature increases. These consistent characters have simplified construction of the correction chart, which has been prepared for the manual already mentioned.

#### *Relation between soil moisture and soil-unit resistance*

Several typical soil-moisture calibration curves are presented in figure 4. The data for these curves were obtained by the calibration method described by Kelley (6), using blocks of soil (weighing approximately 100 gm., oven-dry) enclosed in screen-sided monel boxes. All soil blocks were saturated with distilled water and dried once without measurement of moisture or resistance to settle the soil into a stable volume. This procedure was successful in all soils except the Altamont clay, which settled somewhat during the second drying cycle (shown as the first measured drying cycle in the figure). The resistances have all been corrected for temperature differences.

The four curves are notable in several respects. First, they indicate the wide range of moisture contents over which the soil unit is useful. Moistures as high as pore-space saturation can be detected, as can moistures well below the wilting point. The lower limit of moisture indication is set only by the meter, which, in its present form, will not measure resistances greater than about 3 megohms.

Second, the curves all have a characteristic linked-sigmoid shape. It seems probable that this shape is related to the distribution of pore sizes in the moisture-sensitive fiberglass and to the fiberglass pore space occupied by water at different soil-moisture levels. The resistance measurements are made within a material of constant composition, the moisture content of which is dependent (except for the effect of varying solute concentration) upon the moisture tension rather than the moisture content of the soil enclosing it. Hence, within a tolerance not yet ascertained, the resistance of the fiberglass element is an indication of soil-moisture tension. The shape of each curve is therefore a function of moisture tension, whereas the position of any point along the curve is a function of the moisture content of a particular soil.

Third, figure 4 shows that pore-space saturation, field capacity, and wilting point, each falls within a relatively small resistance range for the four soils studied. Thus at saturation, resistances are in the neighborhood of 150 ohms; at field

capacity they range from 600 to 1,000 ohms; at wilting point they fall between 30,000 and 100,000 ohms. If these consistencies hold for a wider range of soils, it may be possible to use the soil units without previous calibration for studies in which levels rather than exact measurements of soil moisture are to be determined.

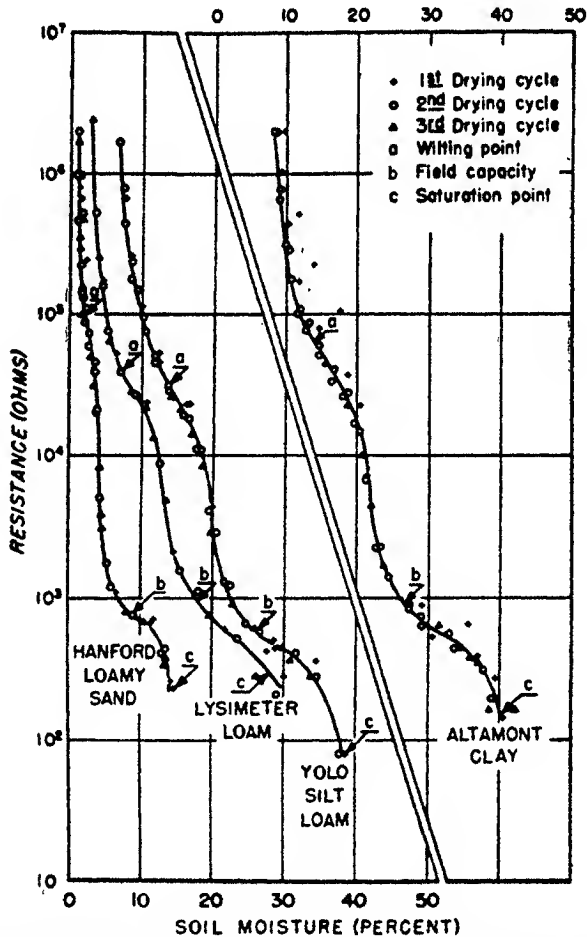


FIG. 4. CALIBRATION CURVES FOR SOIL UNITS PACKED IN FOUR SOILS

Each curve is based on points derived from three drying cycles. (Soil moisture scale for Altamont clay at top of figure.)

#### *Detection of freezing and thawing of soil water*

In the earlier report (3) it was suggested that the soil unit could be used to determine whether soil water was in the solid or the liquid phase. It was also proposed that the unit might be used to detect freezing or thawing of water in a snow pack. These suggestions were made because it was noted that the resistance of a water-saturated soil unit increased markedly when the water in the unit had been frozen. It is possible now to offer some more definite information on this point.



Figure 5 presents the resistance: temperature relations of seven soil blocks, representing a wide range in moisture levels, within the temperature range 10 to 60 ° F. The data in this figure form an extension below 30° of the data shown in figure 3. Only seven of the soil blocks used in that figure have been included in this one, to avoid the confusion of too many lines.

The lines representing each soil block are numbered so that they can be followed from the thawed to the frozen state. Thus it will be noted that the resistance of block 10, representing a completely saturated soil, rises from 120 to

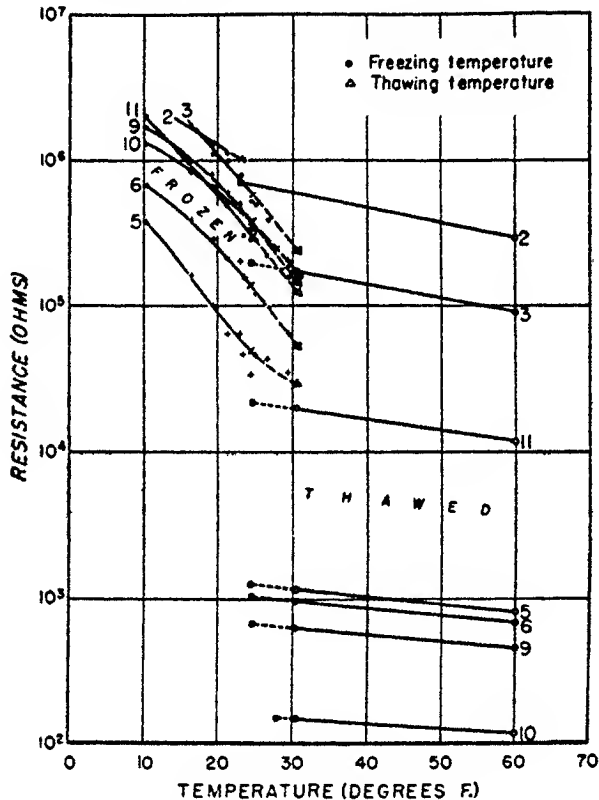


FIG. 5. RESPONSE OF SOIL UNITS TO FREEZING AND THAWING IN SOILS HELD AT DIFFERENT MOISTURE CONTENTS

Each numbered line represents a different soil block

150 ohms as the temperature drops from 60 to 28° F. At 28° the soil moisture freezes, and the resistance rises abruptly to 250,000 ohms. Dropping the temperature to 10° F. brings the resistance up to 1.3 megohms, showing that the increase in resistance per degree change in temperature is much greater in ice than in liquid water. Block 5 represents a soil at about field-capacity moisture. It freezes at a lower temperature, 24.5 degrees, and upon freezing its resistance rises from 1,250 to 50,000 ohms. This rise is considerably less than that of the saturated soil, but it is still sufficient to distinguish between the frozen and the liquid state of the soil water. Block 3 is near the wilting point; while at the

freezing temperature but still unfrozen, its resistance is about 200,000 ohms. Upon freezing at the same temperature, its resistance rises to 600,000 ohms. Figure 4 shows that a small moisture change corresponds to a large change in resistance at moistures near the wilting point. Therefore, the detection of freezing and thawing at this moisture level becomes subject to question. It may be concluded, however, that reasonably reliable detection of freezing and thawing can be achieved by this method in soils that contain more than wilting-point moisture.

Apparently both supercooling and superheating occur in the soils studied. Figure 5 shows that the freezing temperature, indicated by an abrupt rise in resistance, was 2 to 6° lower than the thawing temperature, indicated by an abrupt drop in resistance. The chamber in which this study was made was held at each temperature level long enough that resistance measurements became constant, and the temperature was decreased in 1-degree steps. It is not likely, therefore, that the lapped lines represent a time lag, but rather that they indicate true supercooling and superheating.

This freezing study suggests that the soil-moisture instrument can be extremely useful in field studies. It is well known that soil water does not freeze at 32° F., but rather that its freezing point decreases as moisture content decreases or as solute concentration increases. But no process has yet been devised that will enable one to predict the freezing temperature of a soil in its field position. The soil unit can provide a direct indication of the state of the water within it, and therefore also of the water in the soil around it, for the water in the soil unit is bound to that in the soil in dynamic and chemical equilibrium.

#### *Relation between soil-moisture tension and soil-unit resistance*

Research workers are becoming increasingly aware of the importance of measuring soil-moisture tension in many of their studies. In the high moisture range, from saturation down to somewhat below field capacity, tensiometers provide a direct measure of moisture tension. These instruments fail to function, however, at tensions as great as 1 atmosphere (1,000 cm. of water). The fact that moisture in the fibreglas sandwich of the soil unit is in dynamic (tension) equilibrium with moisture in the soil about it, leads to the suggestion that the soil unit may be used as an indicator of soil-moisture tensions through the entire soil-moisture range from saturation to air-dryness.

An attempt was made to relate soil-unit resistance directly to soil-moisture tension. A porous tension plate (4) was equipped so that moisture tension could be held at any level between 0 and 0.9 atmosphere. Saturated soil blocks, each containing a soil unit, were placed on the plate, and soil-unit resistance was measured as the moisture tension was increased by small increments. When moisture equilibrium had been attained at each tension level, a soil sample was removed from the plate for moisture determination. In this way a moisture-tension graph and a resistance-tension graph could be prepared within the 1-atmosphere tension range. The difficulty encountered in this study was that the resistance-tension graphs were not the same in repeated tension cycles. After

several cycles had been completed it became clear that leaching of the soil block was changing the solute concentration of the soil, so that no consistent resistance-tension relations could be determined.

For resistance-tension relations at higher tensions (up to 15 atmospheres) Richards' pressure membrane equipment was used (7). Model-engine spark plugs served as pressure-tight, insulated leads through the wall of the pressure chamber. In this case, soil moisture and resistance were measured at moisture tensions between 0.7 and 15 atmospheres. Here too the relationship was found

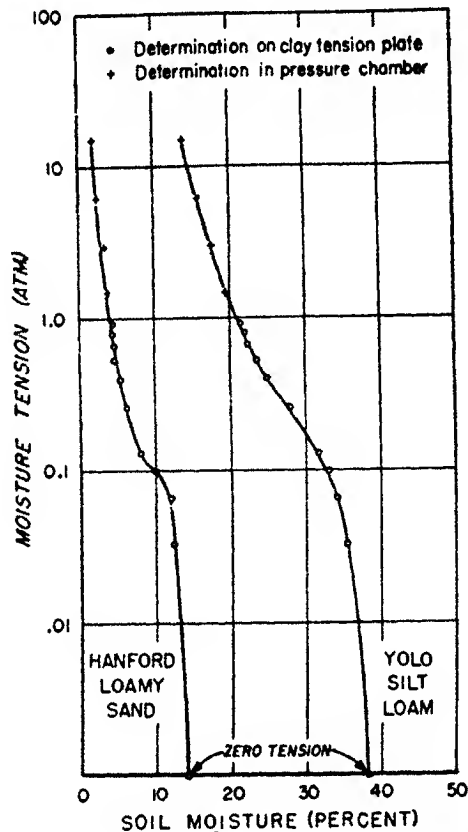


FIG. 6. RELATION BETWEEN SOIL-MOISTURE TENSION AND MOISTURE CONTENT OF TWO SOILS

to be inconsistent, for the resistance of the soil unit appeared to be affected by either the pressure or the high nitrogen content of the chamber.

From such trials as were made, it became apparent that no direct method could be used for relating soil-unit resistance to moisture tension. Hence, an indirect method was employed.

Reliable and reproducible moisture:tension relations were determined from the moisture samples taken on the tension plate and in the pressure chamber. These relations are shown for two soils in figure 6. For the same two soils,

moisture:resistance relations were available in the form of the calibration curves of figure 4. Because the latter relations were determined with soils dried by evaporation, there was no leaching of solutes from the soil, and no shift in calibration curves during successive drying cycles. Developing the resistance:tension relation, then, required reading from the two figures the resistance and tension corresponding to the same moisture content, and plotting these values one against the other. The result is shown in figure 7, which, though admittedly based upon indirect evidence, may yet be of considerable use in soil-moisture investigations. There is always, of course, the excellent possibility of check-

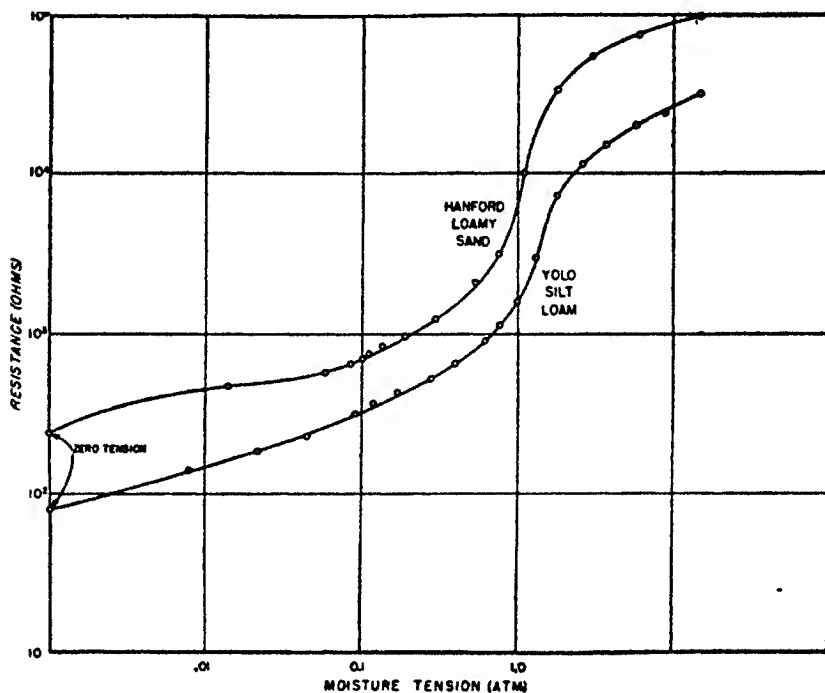


FIG. 7. RELATION BETWEEN SOIL-MOISTURE TENSION AND SOIL-UNIT RESISTANCE, ESTABLISHED BY PLOTTING THE DEPENDENT VARIABLES IN FIGURES 4 AND 6

ing the lower (less than 1 atmosphere) part of the curve in the field by installing tensiometers alongside the soil units.

#### *Uniformity of the soil units*

It has been mentioned that the present design of the soil unit permits close manufacturing uniformity in the thickness and water-retention characteristics of the moisture-sensitive element. One may inquire, however, as to what uniformity in soil moisture:resistance relations would result from this manufacturing control. This question was studied on five soil units chosen at random from a lot of 50.

Each unit was placed in a separate 100-gm. sample of the same air-dry soil, which was packed to uniform apparent density in a screen-sided box of the type

used in moisture calibration. All five soils were wetted and dried once, after which moisture:resistance relations were determined by the method of Kelley.

The results are given in figure 8, where the moisture:resistance relation of each soil unit is shown by a distinctive set of plotted points. The line drawn through the mass of points represents the mean calibration curve of the five soil units.

Within the available moisture range (from wilting point to field capacity) the five units are in excellent agreement. Only one point in this range lies more than a  $\frac{1}{2}$  per cent of moisture from the mean curve, and most points show con-

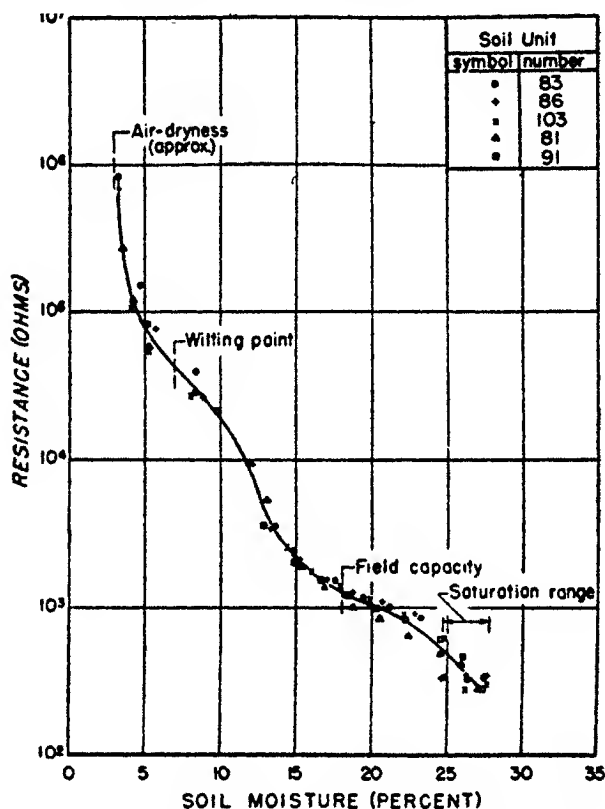


FIG. 8. SOIL MOISTURE: RESISTANCE RELATIONS OF FIVE SOIL UNITS IN SEPARATE BLOCKS OF THE SAME SOIL

Calibration curve represents mean relation

siderably less deviation. At moistures below wilting point, agreement is also excellent, the maximum deviation being about  $\frac{1}{2}$  per cent. Between field capacity and saturation (which, because of slight packing differences, ranges from 24 to 28 per cent) the scatter of points about the mean curve is somewhat greater, deviations of more than 1 per cent being not uncommon. From the range in saturation moistures it is difficult to tell whether this increased scatter is due to differences among soil units or to differences in macropore characteristics of the five packed soils.

The general small scatter of points about the mean curve is encouraging, for

it indicates that close uniformity in moisture and electrical characteristics has been attained in the design and construction of the soil units. If further studies show this degree of uniformity to be typical, the way may be opened for a considerable simplification in the technique of calibrating soil units in terms of soil-moisture content or moisture tension.

*Effect of quality of water upon soil-moisture calibration curves*

All regular laboratory determinations of soil moisture:resistance relations have been made in soil blocks wetted with distilled water. Early measurements showed that if the local tap water was used, salts accumulated in the soil as the

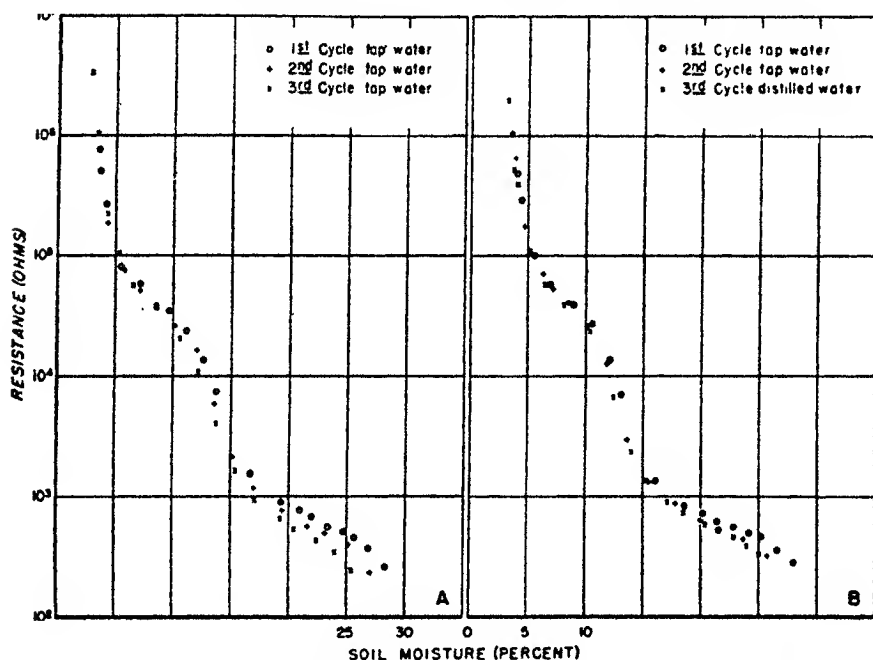


FIG. 9. SOIL MOISTURE: RESISTANCE RELATIONS OF TWO SIMILAR SOILS, SHOWING THE EFFECT OF WETTING WITH TAP AND DISTILLED WATER

Tap water was used in the three cycles shown on the left. Distilled water was used in the third cycle shown on the right, following tap water used in the first and second.

water evaporated, with the result that upon successive drying cycles the resistance of the soil unit decreased at corresponding moistures. As an example of this kind of reaction, the contrasting effects of tap and distilled water are shown in figure 9. The two sets of calibration curves shown were developed by the method already described. Tap water with a specific conductivity of 403 micromhos/cm. was used in the three drying cycles of the soil block shown on the left. For cycles shown on the right, the same kind of soil was wetted with tap water in two cycles, but with distilled water in the third. In both soil blocks resistance decreased at corresponding moistures between the first and second cycles. In the third tap-water cycle a further decrease in resistance was noted.

But when distilled water was substituted in the other block, no significant decrease in resistance was found.

Further evidence of the greater uniformity achieved by use of distilled water is to be found in the calibration curve for lysimeter soil in figure 4. Distilled water was used in the three drying cycles represented in this curve; no shift in resistance is apparent.

It is recommended that laboratory calibrations be made with distilled water. This will ensure the best calibration curve for the soil units when they are installed in field locations where rainfall is the source of soil moisture. Absorption by vegetation and percolation of water through the soil prevent or minimize accumulation of salts, which causes calibration troubles in small soil blocks wetted with tap water in the laboratory. Present experience has not shown the correct laboratory calibration method to be used on soils which vary in soluble salt content during the year, or on those which are irrigated with water high in salts. It appears best now to calibrate units to be used under these conditions directly in the field locations they will occupy. This calls for periodic moisture sampling around the installed units and concurrent resistance measurements, continued until sufficient graphical points have been obtained to define the moisture:resistance curve. Suggestions for the conduct of such a calibration test are included in the manual (5).

#### SUMMARY

The soil-moisture instrument consists of two parts: the soil unit, which includes a monel screen fiberglass-cloth sandwich sensitive to soil moisture, and a thermistor for temperature detection; and the meter unit, which is a battery-powered alternating current ohmmeter. Studies of this instrument made during the last 2 years have shown that:

1. Temperature-induced changes in the resistance of the sandwich are the same for a variety of soils;
2. Soil moistures can be measured from pore-space saturation to well below the wilting point;
3. The instrument will indicate freezing and thawing in soils containing more than wilting-point moisture;
4. By indirect means a calibration curve can be constructed so that moisture tensions can be related to resistance measurements;
5. A random lot of manufactured soil units are closely uniform in their moisture: resistance relations; and
6. Distilled water should be used in laboratory calibrations of soil units to be placed in field soils.

The soil and meter units, uniform in materials and manufacture, are now available. Further testing is needed to show the range of conditions under which the instrument performs satisfactorily and methods by which it can be used to best advantage.

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# ESTIMATION OF CATION-EXCHANGE CAPACITY AND EXCHANGEABLE Ca, K, AND Na CONTENTS OF SOILS BY FLAME PHOTOMETER TECHNIQUES<sup>1</sup>

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Although this laboratory has had a great deal of experience with flame photometer techniques as applied to analyses of plants,<sup>2</sup> it was found necessary to revise the procedures when these techniques were employed on soil extracts. One reason for this lies in the much wider ratios of Ca to K and to Na in soil extracts than in plant digests. Another important factor was the concentration of each of the elements in the extract. It was thought that others might benefit by our experience. Accordingly, this paper describes the instruments and methods used.

## INSTRUMENTS AND ANALYTICAL PROCEDURES

In this laboratory, a Perkin-Elmer flame photometer, model 52A, equipped with acetylene burner and supplied with interchangeable red and blue photocells, is being used for determination of Ba, Ca, K, and Na. Mg is estimated with a Beckman spectrophotometer.

### *Preparation of extract for determining cation-exchange capacity*

Place a 10-gm. sample of air-dried, 2 mm.-sieved soil on a 12.5-cm. Whatman No. 2 filter paper, and leach with successive portions of *N* neutral BaAc solution to 500 ml. Pour 10 ml. of a 10 per cent BaCl<sub>2</sub> solution over the soil sample in the filter, and wash out the excess Ba with distilled water, as indicated by the absence of chlorides. Displace the adsorbed Ba with 0.05 *N* HCL to a volume of 500 ml. Concentrate the solution containing the displaced Ba to a volume of less than 100 ml., cool, transfer to a 100-ml. volumetric flask, and dilute to volume.

### *Flame photometer estimation of Ba*

Pipette a 50-ml. aliquot into a 100-ml. volumetric flask, add 10 ml. 250 p.p.m. Li as LiCl solution, and dilute to 100 ml. The solution is now ready for the estimation of Ba.

Warm the flame photometer containing the blue photocell for at least  $\frac{1}{2}$  hour prior to its use. Locate the position of the Ba line on the wavelength scale with

<sup>1</sup> Paper of the Journal Series, New Jersey Agricultural Experiment Station, Rutgers University—the State University of New Jersey, department of soils.

<sup>2</sup> Toth, S. J., *et al.* Rapid quantitative determination of eight mineral elements in plant tissue by a systematic procedure involving the use of a flame photometer. *Soil Sci.* 66: 459-466, 1948.

a solution containing 750 p.p.m. Ba as  $\text{BaCl}_2 \cdot 2\text{H}_2\text{O}$ . With the location established, reset the machine for indirect method of determination, using 25 p.p.m. Li as the chloride for internal standard. Set the 750 p.p.m. Ba solution containing 25 p.p.m. Li at 100, and check one point on the curve to be sure that the instrument is working satisfactorily. A 375 p.p.m. Ba solution should read 50 scale divisions when the 750 p.p.m. Ba solution is set at 100. Pour unknowns into the funnel of the flame photometer and record the scale readings. Read parts per million Ba in solution from the standard Ba curve.

$$\frac{\text{p.p.m. Ba} \times 2}{68.7} = \text{m.e. Ba per 100 gm. soil}$$

*Preparation of extract for determining exchangeable Ca, Na, and K*

Extract exchangeable bases from a 25-gm., air-dried, 2-mm.-sieved soil, by the method of Schollenberger.<sup>3</sup> Evaporate the extract to dryness on a hot plate, and digest with a mixture of  $\text{HNO}_3$  and  $\text{HClO}_4$  until colorless. The solution should never be allowed to go to dryness at this point. Add distilled water to the digest, bring to a boil, and filter through a Whatman No. 40 filter paper into a 100-ml. volumetric flask. Wash silica with hot water to about 75 ml. Cool, dilute to 100 ml. Discard dehydrated silica.

*Flame photometer estimation of Ca, Na, and K*

Pipette an aliquot of solution containing exchangeable cations into a 100-ml. volumetric flask. The aliquot should contain less than 100 p.p.m. Ca when made to volume. Add 10 ml. 250 p.p.m. Li as  $\text{LiCl}$  solution, and dilute to 100 ml. The solution is now ready for the estimation of Ca and K.

*Calcium (Procedure I).* Warm the flame photometer containing the blue photocell for at least  $\frac{1}{2}$  hour prior to its use. Locate the position of the Ca line on the wavelength scale (4,200 Å.) with a solution containing 100 p.p.m. Ca as  $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ . With the location established, reset the instrument for the indirect method of determination, using 25 p.p.m. Li as the chloride for internal standard. Set the 100 p.p.m. Ca solution containing 25 p.p.m. Li at 100, and check one point on the curve to be sure that the machine is working satisfactorily. A 50 p.p.m. Ca solution should read 50 scale divisions when the 100 p.p.m. Ca solution is set at 100. Pour the unknown into the funnel of the flame photometer, and record the scale reading:

$$\frac{\text{p.p.m. Ca} \times 0.8}{20} = \text{m.e. Ca per 100 gm. soil}^4$$

*Calcium (Procedure II).* If Ca readings are less than 10 p.p.m., the following procedure should be used, for greater accuracy.

Use the diatomic Ca line (5,450 Å.) located on the wavelength scale near the

<sup>3</sup> Schollenberger, C. J., and Simon, R. H. Determination of exchange capacity and exchangeable bases in soil: ammonium acetate method. *Soil Sci.* 59: 13-24. 1945.

<sup>4</sup> When aliquot used is equivalent to 12.5 gm. soil.

Ba line. Follow Procedure I, except that the Ca standard of 20 p.p.m. should be set at 100.

$$\frac{(\text{p.p.m. Ca} - \text{p.p.m. correction for Na}) \times 0.8}{20} = \text{m.e. Ca per 100 gm.}^4$$

*Sodium.* The solution to be analyzed should not contain more than 25 p.p.m. Ca. This can be attained by diluting a portion of the solution used for the Ca determination and adjusting the Li concentration to 25 p.p.m.

Locate the position of the Na line on the wavelength scale, using a solution containing 10 p.p.m. Na as NaCl. With the location established, reset the instrument for the indirect method of determination, using 25 p.p.m. Li as the chloride for the internal standard. Set the 10 p.p.m. Na solution containing 25 p.p.m. Li at 100, and check one point on the curve. A 5 p.p.m. Na solution should read 53 scale divisions when a 10 p.p.m. Na solution is set at 100. Pour the unknown into the funnel of the flame photometer, and record the scale reading. Read p.p.m. Na from the curve, subtract the blank, and multiply by 0.1 to get mgm. Na. Then calculate as follows:

$$\frac{\text{mgm. Na} \times \text{dilution factor to 100 gm.}}{23} = \text{m.e. Na per 100 gm. soil.}$$

*Potassium.* The solution for the analysis of K should contain less than 100 p.p.m. Ca. Normally, the solution used for the estimation of Ca is suitable for the K analysis.

Remove the blue photocell from the instrument and replace it with the red photocell. Warm the flame photometer and locate the position of the K line on the wavelength scale with a solution containing 20 p.p.m. K as KCl. With the location established, reset the instrument for the indirect method of determination, using 25 p.p.m. Li as the chloride for internal standard. Set the 20 p.p.m. K solution containing 25 p.p.m. Li at 100, and check one point on the curve. A 10 p.p.m. K solution should read 43 scale divisions when the 20 p.p.m. K solution is set at 100. Pour the unknown into the funnel of the flame photometer and record the scale reading. Read the p.p.m. K from the standard curve, subtract the blank, and calculate as follows:

$$\frac{\text{p.p.m. K} \times 0.8}{39.1} = \text{m.e. K per 100 gm. soil}^4$$

#### *Estimation of exchangeable Mg*

The Mg content of the soil extract can be determined by the method of Mikkelsen<sup>5</sup> or by the one previously outlined by this laboratory. The latter method is preferred because, once the interfering ions have been removed from the extract, it is possible to choose a proper sized aliquot for estimating Mg. With the Mikkelsen procedure, it is necessary, if the sample is too low or too

<sup>5</sup> Mikkelsen, D. S., Toth, S. J., and Prince, A. L. Determination of magnesium by thiazol yellow method. *Soil Sci.* 66: 385-392, 1948.

high in Mg, to repeat removal of interfering ions by tungstate precipitation on a separate aliquot.

### RESULTS AND DISCUSSION

The estimation of cation-exchange capacity of soils by the procedure outlined is rapid and accurate with soils that do not contain free  $\text{CaCO}_3$ . Table 1 contains the cation-exchange values obtained on 12 soils by precipitation as  $\text{BaSO}_4$  or by the flame technique. The maximum difference between the two values for the nine acid soils was 0.7 m.e. per 100 gm. The values obtained by the flame technique on the three soils that were derived from limestone or lime shale and

TABLE 1

*Comparison of cation-exchange capacity values of soils by a standard method and by the flame photometer technique*

SOIL	HORIZON	pH	EXCHANGE CAPACITY*		RECOVERY†
			Flame	Precipitation	
			m.e.	m.e.	per cent
Norton.....	A	4.50	20.1	19.8	101.5
Annandale.....	A	4.55	10.8	11.3	95.5
Colts Neck.....	A <sub>1</sub>	4.20	9.9	9.9	100.0
Palmyra.....	A <sub>1</sub>	6.85	12.1	11.4	106.1
Collington.....	A <sub>1</sub>	4.65	15.7	15.9	98.7
Bermudian.....	A	6.05	13.9	13.2	105.3
Lakewood.....	A <sub>1</sub>	4.40	2.4	2.7	88.8
Sassafras.....	A <sub>1</sub>	4.50	8.2	7.9	103.7
Hoosic.....	B <sub>1</sub>	5.50	5.2	5.6	92.8
Hagerstown†.....	A	7.65	90.6	16.5	—
Copake†.....	A <sub>p</sub>	7.40	196.9	8.5	—
Dutchess†.....	A <sub>p</sub>	7.20	20.7	14.8	—
Average.....					99.1

\* Per 100 gm.

† Recovery =  $\frac{\text{Flame}}{\text{Precipitation}} \times 100$ .

‡ Contain free  $\text{CaCO}_3$ ; not included in average.

that contained free  $\text{CaCO}_3$  are too high. During the displacement of adsorbed Ba by 0.05 N HCL from these soils, the free  $\text{CaCO}_3$  becomes soluble in the acid and passes into the extract. In the estimation of the Ba content of this extract, both the Ca and Ba ions become activated in the acetylene flame, and the values obtained are several times too high. Because of this, the procedure outlined should be applied only to soils that do not contain free  $\text{CaCO}_3$ .

The content of exchangeable Ca and K of 11 soils, as determined both by flame techniques and by standard chemical procedures, are presented in table 2. In addition, the exchangeable Mg contents of seven soils as determined by the thiazol yellow method are compared with values obtained by precipitation and ignition to  $\text{Mg}_2\text{P}_2\text{O}_7$ . The Na values are those obtained by flame technique.

Excellent agreement for Ca and K between the flame technique and the standard procedures for these elements is shown in the data. The K results are in line with those reported by Mehlich<sup>6</sup>. Values obtained by the flame technique are believed to be more reliable than those determined by the cobaltinitrite method. Agreement between the results obtained by the two methods for Mg is excellent.

Estimation, by flame techniques, of displaced Ba in extracts of acid soils does not present any difficulty. The extract contains chlorides of Ba, Fe, and Al. The last two cations are dissolved by the 0.05 *N* HCL used to displace the adsorbed Ba. These elements need not be removed from the extract prior to the

TABLE 2

*Comparison of some exchangeable cation contents of soils by standard methods and by flame photometer techniques*

SOIL	Ca			K			Mg			Na
	Flame	Oxalate	Recovery*	Flame	Cobaltinitrite	Recovery*	Thiazol Yellow	Pyrophosphate	Recovery*	Flame
	m.e.†	m.e.†	per cent	m.e.†	m.e.†	per cent	m.e.†	m.e.†	per cent	m.e.†
Hagerstown . . .	12.80	12.90	99.2	0.18	0.21	85.7	4.30	4.21	102.1	0.10
Norton . . . . .	0.41	0.36	87.8	0.41	0.40	100.9	—	—	—	0.05
Annandale . . . .	1.62	1.58	102.5	0.14	0.17	82.3	1.72	1.85	92.9	0.05
Colts Neck . . . .	0.24	0.20	102.0	0.12	0.13	92.3	—	—	—	0.03
Palmyra . . . . .	6.00	6.14	97.7	0.17	0.18	94.4	3.20	3.17	100.9	0.02
Copake . . . . .	8.00	8.05	99.3	0.13	0.14	92.8	—	—	—	0.03
Collington . . . .	4.72	4.45	106.0	0.50	0.48	104.1	1.28	1.28	100.0	0.05
Bermudian . . . .	6.40	6.44	99.3	0.15	0.18	83.3	3.20	3.35	95.5	0.10
Lakewood . . . . .	0.06	0.07	85.7	0.01	0.01	100.0	0.07	0.07	100.0	0.04
Sassafras . . . . .	0.37	0.45	82.2	0.20	0.23	86.3	—	—	—	0.02
Hoosic . . . . .	2.28	2.36	96.3	0.06	0.07	85.7	0.70	0.65	107.6	0.04
Average . . . . .			96.1			91.5			99.8	

\* Recovery =  $\frac{\text{Flame}}{\text{Standard procedure}} \times 100$ .

† Per 100 gm.

estimation of Ba, since they do not become sufficiently activated in the acetylene flame to interfere. Determination of Ba in the extract by flame techniques consists only of preparing a standard curve for Ba and reading the values of unknowns from this curve. Studies of the relationship between Ba concentrations and scale readings have shown it to be linear in nature, at least up to 750 p.p.m. Ba, using the internal standard procedure.

The exchangeable-cation extract from soils, after digestion with HNO<sub>3</sub> and HClO<sub>4</sub>, and removal of SiO<sub>2</sub> by filtration, contains Ca, Mg, K, Na, Fe, and Al as chlorides. Possibility of interference of Al, Fe, and Mg in the analyses can be ignored, since these elements are not sufficiently activated by the acetylene

<sup>6</sup> Mehlich, A. Determination of cation- and anion-exchange properties of soils. *Soil Sci.* 66: 429-445. 1948.

flame to interfere. Analysis of the extract for Ca, Na, and K resolves itself into preparation of standard curves for each element, at concentration ranges that might exist in the extracts, and then examination into the influence of other cations alone and in mixtures upon these standard curves.

Some prior knowledge of the base status of soils is necessary for determining the proper concentrations to be used for each cation in preparing standard curves. To illustrate, it might be well to consider the relative concentrations of Ca, K, and Na that exist in extracts of virgin and of cultivated soils of the podzolic area. With soils of this zone, the concentrations of the three elements follow set patterns. Virgin soils are generally acid and contain relatively low concentrations of Ca, Na, and K. Further, the ratio between any two of the cations is not so wide as that encountered in cultivated soils of this area. In cultivated podzolic soils that have been limed to pH 6.5, the concentration of Ca is high, whereas that of both Na and K is relatively low. The ratios of Ca to K and Na are very wide. In view of these facts, it was decided to set an upper limit of 100 p.p.m. for Ca, 20 p.p.m. for K, and 10 p.p.m. for Na in preparing standard curves, since these values approximate the concentrations of each cation that might be found in the exchangeable-cation extracts of a 25-gm. sample of soil.

Standard curves for the three elements, at the concentrations listed, were prepared. The effects of any two cations, alone and in mixtures, were studied on the standard curve of each element.

The results of the study indicated that the standard curve for Ca, with the line at 4,200 Å., was linear and was not affected by 20 p.p.m. K or 10 p.p.m. Na, alone or in mixtures. This is in line with previous studies in this laboratory, in which it was observed that when the ratio of Ca to K was 1:1 or the ratio of Ca to Na was 3:1, the Ca estimation was not affected by the presence of other cations in the extract.

During the analysis of extremely acid podzolic soils in which the calcium saturation was very low, it soon became apparent that the estimation was not most accurate when the standard used contained 100 p.p.m. Ca. Since the sensitivity of the Ca line at 4,200 Å. was weak at Ca concentrations of less than 10 p.p.m., a study was made of the diatomic Ca line at 5,450 Å. The standard curve for Ca, when this extremely sensitive line is used, is linear, but the calcium estimation is affected by the Na concentration in the extract. Fortunately, podzolic soils normally contain less than 0.1 m.e. of Na per 100 gm. and, in the procedure as outlined in the method section, when an aliquot equivalent to 12.5 gm. of soil is used for the determination of Ca, the correction for the influence of Na concentrations on the Ca values can be neglected. The reason for this is that the correction is less than 0.1 p.p.m. Ca. If the diatomic Ca line is to be used when Na concentrations are higher, the proper corrections for the Na effects on Ca values must be established. These corrections are best arrived at by studying the shift of the standard Ca line in the presence of increasing concentrations of Na. A study of this type has shown that a family of curves, paralleling the Ca curve when Na is absent, are obtained. The correction to apply to the unknown samples containing Na represents the difference between the

standard curve with no Na and the Ca curve containing Na. K concentrations up to 20 p.p.m. did not influence the Ca values.

The standard K curve was not affected either by Ca concentrations up to 100 p.p.m. or by Na concentrations up to 50 p.p.m. The curve is not linear, and K values must be read from the curve.

The standard Na curve is linear but, unlike the Ca curve, it does not intersect the zero point of the ordinate and abscissa. Values for Na must be read from the curve. The suggestion, in the methods section, that the Ca concentration in the extract be diluted to 25 p.p.m. or less, prior to determining the Na content of the extract, is based on the results of a study of the standard Na curve in the presence of increasing concentrations of Ca. It had been shown previously that when the ratio of Ca to Na in the extracts was 3:1, the Na values were affected by the Ca concentrations. Our present results indicate that when the ratio of Ca to Na is 2.5:1, Ca does not influence the Na values. It is for this reason that the Ca concentration in the extract is diluted to 25 p.p.m. or less, before the Na content is determined. K concentrations up to 20 p.p.m. did not influence the Na values.

The application of flame photometry to problems in plant and soil analysis is not complicated if the operator using the instrument is aware of the nature of the extracts that are to be analyzed and has prior knowledge of the possible ranges of each cation that may be met with in the course of analyses of different samples. With a knowledge of these facts, flame techniques can easily be developed.

It has been our experience that there is a tendency for the sensitivity of two instruments of the same type to vary considerably. In light of this fact, it is quite possible that the concentration ranges set for the procedure in this study may have to be increased or decreased, depending on the behavior of the instrument.





# RELATIONS BETWEEN SOIL DEPTH AND ACCELERATED EROSION ON THE WASATCH MOUNTAINS

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A study<sup>1</sup> of soils and erosion has been made of selected watersheds on the Wasatch Mountains in northern Utah. The following data and observations, which were derived from that study, point out some of the relations of accelerated erosion to mountain soils and soil depths.

## AREA DESCRIPTION

*Location and size.* This study was made on drainages on the western slopes of the Wasatch Mountains. Six watersheds were mapped. They ranged in size from 6,221 to 18,147 acres and had a total area of 85,593 acres. These watersheds included Box Elder, Farmington, City Creek, Emigration, Lambs, and Big Cottonwood Canyons.

*Physiography.* The Wasatch Mountains are characterized by rugged, maturely dissected topography. Near Salt Lake City and Ogden, they rise abruptly out of the valley plain of Great Salt Lake, the elevation of which is approximately 4,200 feet, to a range of mountains with peaks varying in elevation from 8,500 to more than 11,000 feet.

*Geology.* The part of the Wasatch Mountains studied consists mainly of sedimentary and metamorphic rocks with limestone, quartzite, conglomerate, sandstone, and gneiss predominating. Granite makes up only a small part of the total area. Considerable distortion of the various formations has resulted from complex geologic folding and faulting.

*Soils.* The soils found on these mountainous watersheds are in large part residual in origin but are more or less modified by colluvial effects. Uneroded surface soils are friable, granular, often high in organic matter, and are deep, depths of 10 to 16 inches being common. The subsoils are layers that are transitional between the surface and the weathered parent material, which they strongly resemble. Many of the profiles are stony throughout. The average over-all profile depth to bedrock, excluding rock outcrop areas, varies greatly; but it appears from many observations, that, in terms applied to cultivated lands, most of the soils could be considered as deep and stony. Four to more than 6 feet of soil and soil material over bedrock is the rule rather than the exception.

*Precipitation.* Annual precipitation at the foot of the mountains varies from 16 to 20 inches, whereas the estimated average at the higher elevations is 30 inches, most of which falls as snow.

*Vegetation.* The distribution and the type of vegetation in the watersheds

<sup>1</sup> Made in connection with a U. S. Department of Agriculture Flood Control Survey in 1947.

appear to be determined in large part by climate, as influenced by elevation and aspect. In some instances, soils have also a decided influence; in still others, land use has some effect. Approximately 41 per cent of the area studied is dominantly covered with various kinds of mountain brush (oak, mountain-mahogany, ceanothus). Sagebrush is the next most common vegetative type and is found on 17 per cent of the area. Aspen covers 16 per cent and conifer (spruce and fir) follows with 11 per cent. The annual grass and weed type makes up 4 per cent, and the perennial grass type is found on but 1 per cent. Ten per cent of the area is naturally barren or nearly barren of vegetation.

*Land Use.* The principal function of these watersheds is water production. Recreation and grazing, secondary in importance, are excluded from certain watersheds or portions of watersheds. Because the value of these mountain areas for the production of water is vastly more important than for the production of livestock, the need for moderate grazing use is being increasingly recognized. As a result, the area as a whole is better managed than at any other time since livestock grazing first began.

#### MAPPING UNITS AND PROCEDURE

Because profile difference in these mountain soils due to the kind of parent material was clearly evident and consistent, geologic material was found to be the most useful criterion in classifying the soils into units. A differentiation was also made between deep soils and shallow soils, based on the depth of soil and soil material over bedrock. Twenty-four inches was considered the dividing line between the two phases. The shallow soils varied in depth mainly between 6 and 18 inches, whereas the deep soils were generally more than 36 inches—often more than 6 feet deep.

In this study the many soils encountered were combined into five major groups as follows: 1, deep, friable soils; 2, shallow friable soils; 3, deep soils with tight clay subsoils; 4, shallow soils with tight clay subsoils; 5, rock outcrops. The term *shallow* means shallow to bedrock. The term *friable* is used to designate all soil materials that are readily permeable to water, ranging in this study from sands to firm clay loams. *Tight clay* is the term used for tight or compact silty clay or clays. Brief profile sketches of these groups and the distribution of the erosion classes are shown in figure 1.

Accelerated erosion classes were determined according to the estimated percentage of topsoil lost and comprised three groups. Slight sheet erosion was considered to have occurred on those areas that had lost less than an estimated 25 per cent of the topsoil. The moderate sheet erosion class had lost 25 to 75 per cent of the topsoil. The severe sheet erosion class designated those areas that had lost more than 75 per cent of the topsoil. Gully erosion was found in association with all these classes of sheet erosion. Geologic rock erosion<sup>2</sup> was limited to naturally barren areas such as rock outcrops, cliffs, and coarse talus deposits.

<sup>2</sup> Norton, E. A. Soil Conservation Handbook. U. S. Department of Agriculture Misc. Pub. 352. 1939.

Areas representing the many soil and cover combinations in various stages of erosion were examined intensively. Pits were dug to expose the soil profile, and detailed profile descriptions were written. Portions of the watershed that had similar landscapes were outlined on a watershed base map. These landscape divisions differed in size from 100 to more than 1,000 acres. Within each subdivision of the watersheds so delineated, the areal extent of each vegetative-

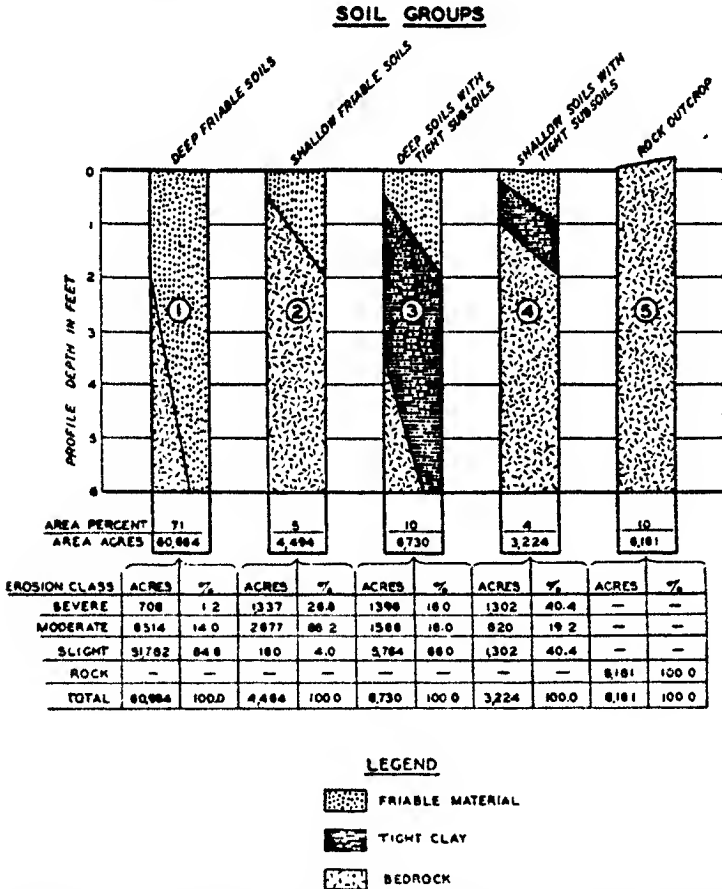


FIG. 1. DIAGRAMMATIC PROFILE SKETCH OF THE FIVE SOIL GROUPS SHOWING RANGE IN DEPTH OF SOIL MATERIALS AND DISTRIBUTION OF EROSION CLASSES

soils-erosion combination was estimated with the aid of aerial photographs and recorded in the field notes.

### RESULTS

Accelerated sheet erosion was found in each of the six watersheds studied. Moderate sheet erosion was found on 16 per cent of the total area, severe sheet erosion on another 6 per cent. These estimates are conservative because it is difficult to determine the exact percentage of surface soil that has been lost. Sixty-eight per cent of the total area was considered to have only slight or no

apparent erosion. Rock erosion was mapped on the rock outcrops comprising the remaining 10 per cent of the land.

Virtually all the accelerated erosion occurs on areas occupied at present by sagebrush, grass, or weed types and on some mountain brush of low density, which occupy approximately 25 per cent of the total area studied. The soils of the conifer, aspen, and heavy mountain brush areas, making up about 65 per cent of the total, have suffered only minor sheet erosion.

The most obvious relation observed between accelerated erosion and soils concerns the depth of friable material over bedrock or tight subsoils. The major soil group of the watersheds mapped is characterized by deep friable soils. It makes up 71 per cent of the total acreage. Only 1 per cent of the land in this group was found to have severe sheet erosion, and only 14 per cent was classified as having moderate sheet erosion. Eighty-five per cent of the land falling in this soil group was considered to have no apparent or only slight accelerated erosion.

The erosion of soils underlain at shallow depths by bedrock or tight clay presents a striking contrast. Of the shallow friable soils with permeable sublayers, nearly 30 per cent are severely eroded along with 16 per cent of the deep soils with tight sublayers and 40 per cent of the shallow soils with tight sublayers. Moderate sheet erosion also occurs on a large portion of these latter three soil groups. Sixty-six per cent of the shallow friable soils were considered to be moderately eroded, as were 18 per cent of the deep soils with tight sublayers, and 19 per cent of the shallow soils with tight sublayers.

Thus, those soils that have friable surfaces underlain by tight clay or bedrock at shallow depths (soil groups 2, 3, and 4) occupy only one fifth of the total area studied, but on them occurred 85 per cent of the severe erosion. Moderate sheet erosion is more widespread over the watersheds than is severe erosion, but a similar trend is still noticeable. Thirty-eight per cent of the moderate sheet erosion mapped is found on these same groups of soil which occupy only one-fifth of the total area.

#### DISCUSSION

Soil studies elsewhere have also shown that soils which are shallow to bedrock or those with tight subsoils are affected more severely by accelerated erosion than are the deeper, more friable types.<sup>3</sup> Reasons why shallow soils are inferior to deep soils are complex but in general are related to limited root space and less available moisture. Soils with tight clay subsoils are handicapped in growing vegetation by their high wilting coefficients and high evaporation losses, which add up to less available moisture. Lack of root space is again a limiting factor.

Because of the poor physical conditions for plant growth, vegetation on shallow soils is not usually abundant and is more easily overgrazed than on deeper-soiled, more productive sites. With the depletion of the vegetation, soil erosion can quickly become accelerated especially under the impact of torrential summer storms. Advanced erosion has already disturbed the infiltration capacity and

<sup>3</sup> Youngs, F. O., *et al.* Soil survey of the Tucson Area, Arizona. U. S. Bur. Chem. and Soils, Soil Surveys, Ser. 1931, No. 19. 1931.

the detention-retention function of some of these soils on watersheds along the Wasatch Front. Because of the soil disturbance, storm water which formerly infiltrated into the soil is increasingly enabled to run off over the surface. Sedimentation rates have, in general, been increased. Instead of delivering steady flows of usable water, several of the canyons have produced damaging floods.

Many of the communities affected by the altered soil-vegetation-water balance on their watersheds are now faced with the problem of restoring that balance. The relation between soil depths and accelerated erosion, based on a classification similar to the one suggested above, is an important determinant of the kind of watershed treatment program to be followed. Treatment of the more critical soils should be given special emphasis. Restabilization of such soils, after erosion, is a slow and difficult process. Elimination or heavy curtailment of the grazing stock is seldom enough to induce recovery in a reasonable time. Additional measures, such as reseeding and contour trenching, are generally necessary to effect restabilization of the shallow soils and those with tight clay subsoils. Proper range management, however, is often the only treatment needed on the deeper, friable soils because of their more favorable conditions for plant growth.



# GROWTH OF LETTUCE AND BARLEY AS INFLUENCED BY DEGREE OF CALCIUM SATURATION OF SOIL

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It has often been observed that serpentine soils do not produce satisfactory yields even after addition of nitrogen, phosphorus, and potassium. Several interpretations have been given to this phenomenon. For many years unfavorable Ca-Mg ratios have been emphasized.

This report approaches the problem of serpentine soils from the standpoint of the exchangeable-cation composition. In particular the concept of the degree of saturation of calcium is emphasized and applied to soils in general. A partial summary of these results has already been published (20).

## EXPERIMENTAL METHODS AND RESULTS

### *Standard nutrient test*

A quantity of Conejo clay soil, derived from outwash material of a serpentine rock area, was obtained near Morgan Hill, California, and submitted to a standard fertility test. Romaine lettuce was used as an indicator of nutrient deficiencies, and a few tests included barley as a representative of the grain family. Six-inch pots were covered with black asphalt paint inside, and with aluminum paint on the outside. Painted saucers were used under the pots to avoid loss of nutrients by leaching. Each pot received 1,600 gm. of soil, and the treatments were replicated four times. The soil was sifted through a half-inch wire mesh and mixed into a homogeneous mass before it was weighed out.

The first four pots consisted of checks, to which no nutrients were added. The next series of four pots comprised the standard complete treatment of nutrients with N added as  $\text{NH}_4\text{NO}_3$ , P as  $\text{Ca}(\text{H}_2\text{PO}_4)_2$ , and K as  $\text{K}_2\text{SO}_4$ . The chemicals, of c. p. grade, were added in solution and were mixed manually with each mass of soil. The rates were such as to correspond on an acre basis (2 million pounds of soil) to 200 pounds of N, 300 pounds of  $\text{P}_2\text{O}_5$ , and 200 pounds of  $\text{K}_2\text{O}$ . These amounts of nutrients have been found to produce maximum yields in pots on a large number of soils. In each succeeding treatment one of the three elements was omitted and the remaining two were added. These partial treatments provided a test of the nutrient-supplying power of the soil for each element in the presence of adequate amounts of the other two. This system will be recognized as a modified Mitscherlich technique.

Romaine lettuce was transplanted from germination flats 18 days after being planted. The seedlings were selected for uniformity in appearance and were planted one per pot. The barley seeds were planted directly at the rate of five per pot. Distilled water was applied on the surface as needed. The plants were

<sup>1</sup> The author is indebted to H. Jenny for suggesting the problem and for his advice throughout the investigation.

grown in the greenhouse for the first 2 weeks and then moved outdoors for the remaining period in an area enclosed by a wire screen. After 42 days of growth in the pots, the plants were harvested and fresh weights of the shoots determined. After drying for 60 hours in a ventilated oven at 70° C, the plants were weighed and these oven-dry weights used as a basis for comparing yields. The results of the standard nutrient test with lettuce and barley on Conejo soil are shown in table 1.

Both lettuce and barley showed striking responses to nitrogen and phosphorus, but the potassium effect was of a small magnitude. These data are in accord with the results of Gordon and Lipman (4) so far as nutrient response to N, P, and K are concerned. The yield of the complete treatment, however, was low compared to the average yields from other soils tested during this season. Of even greater significance was the appearance of a rosette disease consisting of a curling and extreme stunting of the younger lettuce leaves with dark spots along

TABLE 1

*Response of lettuce and barley to N, P, and K treatment of Conejo soil*  
Plants grown in pots from April 15 to May 27, 1947; four pots each treatment

TREATMENT	AVERAGE DRY WEIGHT PER POT	
	Lettuce	Barley
	gm.	gm.
N <sub>0</sub> P <sub>0</sub> K <sub>0</sub> .....	0.44	0.62
N <sub>2</sub> P <sub>2</sub> K <sub>2</sub> *.....	4.44	2.24
N <sub>0</sub> P <sub>2</sub> K <sub>2</sub> .....	0.54	0.44
N <sub>2</sub> P <sub>0</sub> K <sub>2</sub> .....	2.48	1.66
N <sub>2</sub> P <sub>2</sub> K <sub>0</sub> .....	4.02	2.06

\* N<sub>2</sub> is equivalent to 200 pounds N per acre; P<sub>2</sub> to 300 pounds P<sub>2</sub>O<sub>5</sub> per acre; K<sub>2</sub> to 200 pounds K<sub>2</sub>O per acre. N<sub>0</sub>, P<sub>0</sub>, K<sub>0</sub> indicate no addition of these elements.

the edges. Symptoms on barley appeared as a failure of the growing point of the shoot. These symptoms have been observed on several serpentine soils tested in this manner. The low yields and the leaf symptoms obtained even with the complete N, P, and K additions indicated other factors were involved in the unproductive character of this soil.

#### *Effect of minor elements*

In the earlier stages of these experiments, repeated attempts were made to alleviate the rosette symptoms or increase the yields by administration of the elements Mn, B, Zn, and Cu, applied by spraying on the leaves and by addition to the soil. No beneficial effects were observed.

A recent report of Mo deficiency in primary serpentine soil (21) led to the inclusion of this element in a test for minor-element deficiency. Lettuce and tomato were both used as test plants because of their sensitivity to minor-element deficiency. The soils on which they were grown received N, P, and K. Again no improvement was found in yield or symptoms from use of the five minor elements either separately or combined. The use of two sources of nitrogen,







$\text{NH}_4\text{NO}_3$  and  $\text{Ca}(\text{NO}_3)_2$ , likewise failed to produce any indication of minor-element deficiency.

### *Effect of gypsum*

A theory advanced by Loew and May (12) attached considerable importance to the Ca:Mg proportion. A ratio of less than 5:4 was thought to be detrimental to plant growth. This view was based on total analyses of soils. The emphasis on a Ca-Mg ratio was also supported by Novak (16) after an exhaustive survey of the European literature on the subject.

On the other hand, a comparison of a number of acid and neutral soils led Moser (15) to believe that the absolute amount of Ca was the decisive factor rather than a critical Ca-Mg ratio. Another point of view advanced by Robinson *et al.* (18) favored the toxic influence of chromium, nickel, and perhaps cobalt. This was

TABLE 2

*Effect of gypsum and single-salt leaching of Conejo soil on lettuce yield and occurrence of rosette*  
Plants grown in pots from May 31 to July 12, 1947; four pots each treatment

TREATMENT	AVERAGE DRY WEIGHT	DEGREE* OF ROSETTE
	gm.	
$\text{N}_2\text{P}_3\text{K}_2$	4.5	Moderate
Gypsum† + $\text{N}_2\text{P}_3\text{K}_2$	8.6	Trace
Leached with $\text{CaSO}_4$ ‡ + $\text{N}_2\text{P}_3\text{K}_2$	9.1	None
Leached with $\text{MgSO}_4$ + $\text{N}_2\text{P}_3\text{K}_2$	4.0	Distinct
Leached with $\text{K}_2\text{SO}_4$ + $\text{N}_2\text{P}_3\text{K}_2$	4.3	Moderate

\* In increasing order of severity the symptoms are classified relatively as trace, slight, moderate, distinct, and severe.

† Gypsum added at the rate of 3.5 tons per acre.

‡ Leached with 0.02 N  $\text{CaSO}_4$  corresponding to 5 tons gypsum per acre. Other salts used in equivalent amounts.

concluded after a statistical analysis of the chemical composition of a large number of serpentine soils.

In view of the well-established high Mg content of soils derived from serpentine material, a gypsum treatment was added to the complete N, P, and K nutrients. As a further test, additional pots were leached separately with single-salt solutions of  $\text{CaSO}_4$ ,  $\text{MgSO}_4$ , and  $\text{K}_2\text{SO}_4$ . After removal of the excess salts with water, each pot received the standard amounts of nutrients. The yields of lettuce grown on these soils are shown in table 2.

The increase in amount of growth and the improvement in appearance of the plants grown on soils treated with gypsum or leached with  $\text{CaSO}_4$  pointed to a Ca deficiency or a Mg toxicity, or possibly both. The leachings with  $\text{MgSO}_4$  and  $\text{K}_2\text{SO}_4$  resulted in no improvement of yield or appearance of plants.

### *Use of cation-Amberlites on serpentine soil*

To test the several hypotheses already mentioned, an experiment was devised using synthetic exchange materials as carriers of certain cations in the adsorbed

state. These adsorbents afford an opportunity to add some cations to the soil without changing the absolute amounts of the other cations present and without adding anions.

The cation carrier used in this investigation is the type designated as "1R-100 cation-exchange Amberlite." This is a coarse material with an exchange capacity amounting to roughly 150-185 m.e. per 100 gm. oven-dry weight. The various cation-Amberlites were obtained by leaching with single-salt solutions.

Separate pots of soil received Amberlites carrying Ca, Mg, K, and Sr. Initially two rates of application were made, 100 gm. and 200 gm. of cation-Amberlite per pot. These amounts correspond to 6.2 and 12.4 gm. of Amberlite per 100

TABLE 3

*Effect of cation-Amberlites added to Conejo soil with complete N, P,\* and K on yield and leaf symptoms of lettuce and barley*

Plants grown in pots from July 14 to August 25, 1947; two pots each treatment

AMBERLITE TREATMENT PER 100 GM. AIR-DRY SOIL	LETTUCE		BARLEY	
	Average dry weight	Degree of rosette	Average dry weight	Tip failure
gm.	gm.		gm.	
0†.....	3.9	Moderate	2.8	Moderate
6.2 Ca-Amberlite.....	10.5	None	4.6	None
12.4 Ca-Amberlite.....	10.6	None	—†	
6.2 Mg-Amberlite.....	2.9	Distinct	1.4	Distinct
12.4 Mg-Amberlite.....	0.6	Severe	—	
6.2 K-Amberlite.....	3.6	Moderate	2.6	Moderate
12.4 K-Amberlite.....	2.9	Distinct	—	
6.2 Sr-Amberlite.....	4.7	Moderate	3.2	Moderate
12.4 Sr-Amberlite.....	4.0	Moderate	—	

\* Addition of P as calcium phosphate raised the Ca content of this soil by 0.22 m.e. per 100 gm. The negligible effect of this amount of Ca was determined by growing plants with this source of phosphate compared to ammonium phosphate. No differences in size or appearance of lettuce and barley were detected between the two phosphate sources.

† All pots treated with  $N_2P_2K_1$ .

‡ Only one Amberlite rate was used with barley.

gm. air-dry soil, respectively. The standard N, P, and K nutrients were also added. Because of the high cost of Amberlite, the determinations were reduced to two per treatment instead of the usual four. The results of this experiment are given in table 3, including a test with barley in which the 100-gm. addition of Amberlite was employed.

Only the Ca-Amberlite treatment gave a yield that compared favorably with yields obtained on fertile soils. Likewise, it was the only treatment that prevented formation of rosette. The K-Amberlite gave a reduced yield and an aggravated rosette. The Mg-Amberlite produced the smallest plants and the most severe symptoms. The Sr-Amberlite gave a slight increase in yield but no perceptible improvement in appearance. The relative size and the leaf symptoms of the lettuce plants are shown in figure 1.

The exchangeable-cation content of these soils, before and after addition of the Amberlites, is given in table 4. Also given are the cation components found in the shoots of the lettuce plants. The chemical methods of Piper (17) were used except for Sr, which was determined gravimetrically after precipitation as the sulfate.



FIG. 1. LETTUCE PLANTS GROWN ON CONEJO CLAY SOIL OF SERPENTINE ORIGIN SHOWING ROSETTE SYMPTOMS

All pots were given N, P, and K nutrients. The pot on the extreme left received no Amberlite. The remaining pots received 12.4 gm. of the indicated Amberlite per 100 gm. soil.

TABLE 4

*Effect of cation-Amberlites added to Conejo soil\* on composition of exchangeable bases in soil-Amberlite mixtures and of cations in lettuce plants*

AMBERLITE TREATMENT PER 100 GM. SOIL	EXCHANGEABLE BASES IN SOIL					CATION CONTENT OF LETTUCE SHOOTS				
	Ca	Mg	K	Sr	Na	Ca	Mg	K	Sr	Na
	%†	%	%	%	%	m.e.†	m.e.	m.e.	m.e.	m.e.
0.....	12.6	85.4	0.9	0	1.1	16.5	109	137	0	15.3
6.2 Ca-Amberlite .....	27.0	71.3	0.8	0	0.9	27.0	75	68	0	16.8
12.4 Ca-Amberlite .....	35.4	63.4	0.5	0	0.7	34.2	60	55	0	18.2
6.2 Mg-Amberlite .....	11.1	87.3	0.7	0	0.9	14.3	144	103	0	14.7
12.4 Mg-Amberlite .....	10.0	88.8	0.5	0	0.7	10.6	170	47	0	13.9
6.2 K-Amberlite .....	11.7	76.2	11.2	0	0.9	14.9	94	179	0	14.1
12.4 K-Amberlite .....	10.3	67.4	21.5	0	0.8	11.8	66	256	0	12.9
6.2 Sr-Amberlite .....	11.1	73.8	0.8	13.4	0.9	15.6	99	82	7	16.1
12.4 Sr-Amberlite .....	9.8	61.8	0.5	27.2	0.7	11.2	99	65	11	16.7

\* The base-exchange capacity was 44.0 m.e. per 100 gm. oven-dry soil, as determined by displacement of  $\text{NH}_4$  after leaching with ammonium acetate.

† Of total exchangeable bases.

‡ Per 100 gm. oven-dry weight.

The untreated soil as used in these pots had a pH of 7.2 and an exchange capacity of 44.0 m.e. per 100 gm. oven-dry weight. The percentage of Ca present amounted to 12.6. The absolute quantity was 5.5 m.e. Ca per 100 gm. of soil. According to the Amberlite experiment, the causes of the rosette symptoms were eliminated by raising the percentage of Ca to 27.0 (100 gm. Ca-Amberlite addition). However, this treatment, besides raising the degree of saturation of Ca,

simultaneously increased the absolute amount of Ca, and likewise raised the Ca-Mg ratio. Additional experimentation was required to establish which of these factors was predominant in the infertile status of this soil.

The cation analysis of lettuce shoots, shown in table 4, bears out, in general, the improved Ca status of the healthy plants and the lowered Ca content of the plants with aggravated rosette symptoms. The strontium aspect will be discussed later.

#### *Use of cation-Amberlites on a productive soil*

It appeared reasonable to expect that use of various cation-Amberlites as a means of altering the Ca status of a highly productive soil might disclose to what extent the amount of Ca, the degree of Ca saturation, and the Ca-Mg ratio were concerned in the growth of plants. Addition of different cation-Amberlites would make it possible to reduce the Ca saturation without affecting the absolute



FIG. 2. LETTUCE PLANTS GROWN ON A PRODUCTIVE YOLO SOIL SHOWING ROSETTE SYMPTOMS ON MG- AND K-AMBERLITE TREATMENTS

All pots were given N, P, and K nutrients. The pot on the extreme left received no Amberlite. The remaining pots received 17.0 gm. of the indicated Amberlite per 100 gm. soil.

amount present in a soil. This would be done, for instance, by addition of Mg-Amberlite. Likewise, use of K-Amberlite not only would leave the amount of Ca constant, but it would also preserve the same Ca-Mg ratio, while lowering the degree of saturation of Ca.

For this purpose a fertile Yolo clay was supplied with several cation-Amberlites. The complete combination of N, P, and K was added to each pot. Initially, two amounts of Amberlite were used, 100 gm. and 200 gms. per 1,600 gm. of soil, the same amounts as were used on the serpentine soil.

No profound differences either in yield or in appearance were noticeable. The reasons for this became obvious when a base-exchange analysis of the soils receiving the highest rate of Mg-Amberlite still showed a Ca-saturation in excess of 30 per cent. The data from the Conejo soil showed that even 27 per cent Ca when complemented by Mg was sufficient to produce good yields and healthy plants.

A subsequent test was made with Amberlite applications stepped up to a rate

of 275 gm. per 1,600 gm. of soil. Because of difficulty in obtaining sufficient Amberlite at the time, however, 5-inch pots holding only 800 gm. of soil were used, allowing a reduction in the amount of Amberlite required by half. The nutrients N, P, and K were supplied at half the amount also, but the rate per acre remained the same as in the 6-inch pot.

The appearance of the lettuce plants grown in these soils is indicated in figure 2. It will be seen that healthy plants were produced on the pots with no Amberlite, with Ca-Amberlite, and with Sr-Amberlite. The Mg-Amberlite produced an intensity of rosette classified as slight. The K-Amberlite produced a rosette considered distinct by comparison to the Mg treatment. A closeup of a K-Amberlite and a no-Amberlite lettuce plant is shown in figure 3.



FIG. 3. OBLIQUE VIEW OF LETTUCE PLANTS GROWN ON A PRODUCTIVE YOLO SOIL WITHOUT AMBERLITE (left) AND WITH K-AMBERLITE

The dry weights of these plants were given in table 5. The treatment showing the worst rosette symptoms, the K-Amberlite, likewise showed the lowest yields. On the other hand, no significant reduction in weight of the plants was indicated by any of the other treatments.

In appraising these results, the following conclusions were drawn:

1. Appearance of the lettuce rosette on a productive Yolo soil treated with Mg-Amberlite, and correction of this phenomenon on the serpentine soil by addition of Ca-Amberlite, eliminated Cr, Ni, and Co as disease-producing agents.
2. Formation of rosette on the Yolo soil when K-Amberlite was added removed Mg as a primary factor. At the same time it ruled out the absolute level of exchangeable Ca, inasmuch as the amounts of Ca in the pots were the same except for those to which Ca-Amberlite had been added. In other words, the absolute amounts of Ca were not reduced; only the degree of Ca-saturation was altered by the addition of Mg- and K-Amberlites.
3. The primary factor responsible for deficient yields and rosette disease of lettuce grown

on the serpentine soil was the low degree of saturation of Ca. To reduce the percentage of Ca on the base-exchange complex of a fertile soil, either Mg or K adsorbents could be used as sources of the complementary ion. In fact, of these two cations, K was the more effective because of its greater competing power, at a given degree of Ca-saturation, in reducing the Ca content of the plant tissues.

These conclusions are supported by the soil and plant analysis included in table 5. In the presence of Ca-Amberlite the yields were good and no rosette symptoms appeared. Where Mg-Amberlite was added, there was no significant reduction in growth, despite the rosette symptoms, even though slight. The K-Amberlite produced the smallest plants and a very pronounced rosette of the leaves. It should be noted that this inequality in the effects of Mg- and K-Amberlites occurred at approximately equal degrees of Ca-saturation of the soil. The situation may be resolved by reference to the plant analyses. Here

TABLE 5

*Effect of cation-Amberlites added to Yolo soil\* on yield, incidence of rosette, exchangeable bases of soil, and cation composition of lettuce plants*

Plants grown in pots from August 25 to October 6, 1947; two pots per treatment

AMBERLITE TREATMENT PER 100 GM. SOIL	AVER- AGE DRY WEIGHT	DEGREE OF ROSETTE	EXCHANGEABLE BASES IN SOIL					pH OF SOIL (1:2)	CATION CONTENT OF LETTUCE SHOOTS				
			Ca	Mg	K	Sr	Na		Ca	Mg	K	Sr	Na
gm.	gm.		%†	%	%	%	%		m.e.‡	m.e.	m.e.	m.e.	m.e.
0 + 25 gm. sand.....	6.2	None	42.3	51.0	1.5	0	5.2	7.4	59	80	96	0	38
17 Ca-Amberlite.....	6.3	None	65.0	30.8	0.7	0	3.5	7.6	72	49	64	0	38
17 Mg-Amberlite.....	5.9	Slight	23.5	72.5	0.9	0	3.1	7.6	22	94	59	0	51
17 K-Amberlite.....	2.6	Distinct	25.9	29.4	41.3	0	3.4	7.9	12	24	184	0	38
17 Sr-Amberlite.....	6.0	None	24.1	28.8	1.1	42.2	3.8	7.5	21	43	75	26	35

\* The base-exchange capacity of this soil was 33.6 m.e. per 100 gm. oven-dry soil as determined by displacement of  $\text{NH}_4$  after leaching with ammonium acetate. The sum of the bases exceeded this slightly.

† Of total exchangeable bases.

‡ Per 100 gm. oven-dry weight.

it develops that K was much more effective than Mg in reducing the Ca content of the plants. This happened in spite of the higher degree of Mg-saturation compared to K-saturation in the respective Amberlite treatments (due to the higher initial Mg content of the soil).

The effect of Sr-Amberlite suggests a partial substitution of this cation for Ca. This phenomenon has already been recorded by Gedroiz (3), who used leaching technique with various salt solutions. He failed, however, to mention what the ultimate composition of the bases in the leached soils amounted to. It is conceivable that the leaching was not complete in the sense of having removed all the exchangeable Ca. This is mentioned because in this laboratory a leaching of Yolo soil with  $\text{SrCl}_2$  sufficient to reduce Ca to below 10 per cent formed a rosette and reduced the growth of plants. For these reasons, the substitution of Sr for Ca may be considered as partial. The indefinite status of Sr is also reflected in the work reported by Walsh (22) on mustard, oats, barley, and wheat.



*Use of Decalso on a serpentine soil*

A serpentine soil from Contra Costa County had been tested by the standard technique and a definite N and P deficiency revealed. The lettuce plants grown on this soil formed the same type of rosette as has been described for the Conejo soil.

The adsorbed-cation treatment was applied to this soil to determine in what respects it might deviate from the Conejo soil. But in this instance "Decalso" adsorbent<sup>2</sup> was employed. The cations Ca, Mg, Sr, and K were substituted on Decalso by leaching with the respective chlorides. Only the 100-gm. rate of adsorbent was applied to soils furnished with the complete N, P, and K combination. The plants grown on these soils are shown in figure 4. They bear a striking similarity to the plants grown on Conejo soil in which the cation-Amberlites were added. Also in this instance only the Ca-Decalso, of the four types used, increased the yield and eliminated the rosette symptoms. This soil likewise failed



FIG. 4. LETTUCE PLANTS GROWN ON SERPENTINE SOIL SHOWING ROSETTE SYMPTOMS

All pots were given N, P, and K nutrients. The pot on the extreme left received no Decalso. The remaining pots received 6.2 gm. of the indicated Decalso per 100 gm. soil.

to exhibit any response to Mn, B, Zn, Cu, and Mo through the medium of lettuce or tomato plants.

*Water-culture experiments*

An independent check of the results already presented was made by attempting to produce the lettuce rosette in nutrient solutions of known composition.

The basic nutrient solution employed was that of Hoagland. Lettuce seedlings were transplanted to corks inserted in aerated 14-liter tanks. Five solutions were made up providing for several combinations of Ca, Mg, and K. An additional solution containing Sr was abandoned because of impossibility of keeping the salts in solution.

The first tank contained Hoagland's solution, modified by a small addition of  $(\text{NH}_4)_2\text{SO}_4$  to avoid an alkaline drift in pH of the solution. The second solution differed from the first by a reduction in the amount of  $\text{Ca}(\text{NO}_3)_2$  to one tenth and a corresponding addition of  $\text{Mg}(\text{NO}_3)_2$ . This comprised the low-Ca, high-Mg combination. The next solution involved a similar reduction in  $\text{Ca}(\text{NO}_3)_2$

<sup>2</sup> Decalso is a synthetic cation absorbent made by the Permutit Co.

balanced osmotically by a corresponding increase in  $\text{KNO}_3$  to produce a low-Ca, high-K solution. In the fourth tank the  $\text{Ca}(\text{NO}_3)_2$  was reduced, while the other nutrients were left the same. This was the low-Ca solution. Finally, a solution was made with only a one-fifth reduction in  $\text{Ca}(\text{NO}_3)_2$  and an increase in  $\text{Mg}(\text{NO}_3)_2$  equal to that made in tank 2. This solution was described as 2× low-Ca, high-Mg.

All solutions received supplementary nutrients of Mn, B, Zn, Cu, and Mo. Iron as tartrate was supplied once at the start of the growth period. The composition of the major elements in these solutions is given in table 6.

TABLE 6

*Composition of nutrient solutions used to grow lettuce plants in 14-liter tanks*

SALT	CONCENTRATION OF SALT, IN M.E. PER LITER				
	Modified Hoagland's solution	Low-Ca, high-Mg	Low-Ca, high-K	Low-Ca	2× Low-Ca, high-Mg
$\text{Ca}(\text{NO}_3)_2$ .....	10	1	1	1	2
$\text{KNO}_3$ .....	5	5	14	5	5
$\text{MgSO}_4$ .....	4	4	4	4	4
$\text{Mg}(\text{NO}_3)_2$ .....	0	9	0	0	9
$\text{KH}_2\text{PO}_4$ .....	1	1	1	1	1
$(\text{NH}_4)_2\text{SO}_4$ .....	1	1	1	1	1

TABLE 7

*Cation composition of lettuce plants grown in nutrient solutions of various Ca, Mg, and K proportions*

SOLUTION	DEGREE OF ROSETTE	CATION COMPOSITION OF LETTUCE SHOOTS, IN M.E. PER 100 GM. OVEN-DRY WEIGHT		
		Ca	Mg	K
Hoagland's.....	None	77.5	44	116
Low-Ca, high-Mg.....	Distinct	13.0	120	141
Low-Ca, high-K.....	Moderate	14.6	44	199
Low-Ca.....	Slight	17.8	60	168
2× Low-Ca, high-Mg.....	Slight	18.3	88	187

After a growth period of 4 weeks the plants were harvested and analyzed for Ca, Mg, and K. The results are presented in table 7.

This experiment confirmed the conclusions drawn from the tests on soils. The lettuce rosette was induced in solutions low in Ca, regardless of whether there was a corresponding increase in Mg or K. The severity of the symptoms varied inversely with the Ca level in the plants. The lowest Ca content and most severe symptoms appeared in the low-Ca, high-Mg solution, followed in order by the low-Ca, high-K; the low-Ca; and the 2× low-Ca, high-Mg combinations.

#### *Degree of calcium-saturation of soils*

The relative significance of the degree of Ca-saturation of soils as a factor in Ca availability has been demonstrated by the experiments described. On





serpentine soils with a predominant Mg composition of the base-exchange complex, healthy lettuce plants were produced when the degree of Ca-saturation was raised above 25 per cent.

On a normally productive Yolo soil, reduction of the Ca-saturation to below 25 per cent by addition of adsorbed Mg resulted in lettuce rosette symptoms similar to those formed on unaltered serpentine soils. Furthermore, reduction of Ca-saturation in Yolo soil by addition of adsorbed K produced more severe symptoms and smaller plants at a slightly higher degree of Ca-saturation than obtained where adsorbed Mg had been used. Plant analysis revealed this to be due to the greater effectiveness of K in lowering the Ca content of the lettuce plants. These results were achieved on the Yolo soil without appreciably altering the absolute amount of Ca. This, of course, does not affect the conclusions reached by Jenny and Cowan (8) on the effect of limiting amounts of Ca supplied at uniform degrees

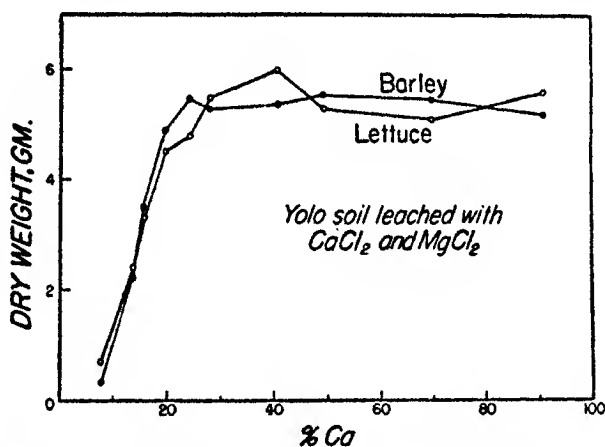


FIG. 5. YIELD OF LETTUCE AND BARLEY AS A FUNCTION OF DEGREE OF CALCIUM SATURATION OF YOLO SOIL

Yolo soil was leached with  $\text{CaCl}_2$  and  $\text{MgCl}_2$  to obtain a wide range of Ca-saturation, with N, P, and K nutrients added.

of Ca-saturation. Our data support the relation of K availability to the degree of saturation and the complementary ion effects found by Jenny and Ayers (10).

To examine more quantitatively the growth of plants as a function of Ca-saturation, Yolo soil was leached with  $\text{CaCl}_2$  and  $\text{MgCl}_2$  to give a wide range of values. These varied from a low of 7.9 per cent Ca-saturation to a high of 91.0 per cent. The remainder of the cation content was largely made up of Mg. The amounts of K and Na present added up to about 1 per cent of the total.

The soils were placed in 5-inch pots and each received the standard amounts of nutrients. Lettuce and barley plants were grown by the methods already described. The results obtained are represented graphically in figure 5.

Both lettuce and barley show a similar rapid decline in yield as the degree of Ca-saturation falls below 20 per cent. Above that point the two curves tend to flatten off, and the variation is more marked since the Ca-saturation is no longer decisive and other factors have entered the picture.

These curves are very similar to those in figure 6 for lettuce and barley grown on Conejo soil with various amounts of Ca- or Mg-Amberlite.

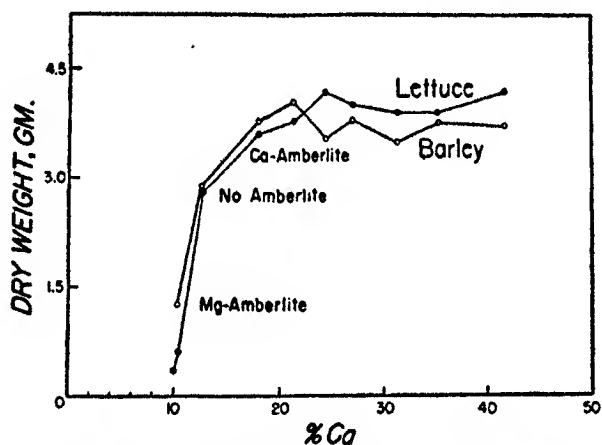


FIG. 6. YIELD OF LETTUCE AND BARLEY AS A FUNCTION OF DEGREE OF SATURATION OF CALCIUM IN CONEJO SOIL

The Ca-saturation of the natural soil was raised by addition of Ca-Amberlite and lowered by addition of Mg-Amberlite. Nutrients of N, P, and K were added.

#### DISCUSSION

The results of this investigation confirm the earlier reports of Jenny and Cowan (9) and of Jarusov (6, 7) concerning the availability of Ca as a function of the degree of saturation. This is shown by the sharp reduction in plant growth when the degree of Ca-saturation falls below 20 per cent if Mg is the complementary cation. The results also support the concept of cation availability as a function of ease of replacement of the complementary ion (10). This is shown by the greater effectiveness of K compared to Mg in reducing Ca uptake.

The work herein reported is at some variance with that of Horner (5), Albrecht (1), Allaway (2), Mehlich and Colwell (13), and Mehlich (14), who obtained increases in growth at Ca-saturations above 40 per cent using Ca-H systems. The explanation of this discrepancy may lie not only in the nature of the complementary ion (H), but also in the amount of Ca supplied. It has been shown (8) that even in the presence of a high degree of Ca-saturation, limited amounts of Ca may restrict plant growth. The authors referred to above used clay-sand mixtures with small amounts of Ca per unit of mixture. It is possible they were testing degree of saturation at a level where the amount of Ca was still limiting. This contingency was avoided in the present work by use of soils containing large amounts of Ca at the various degrees of saturation. Likewise they did not examine the zone of Ca-saturation that we have found to be the most severely limiting for plant growth, the zone below 20 per cent Ca-saturation.

The discussion has thus far centered on the manifestations of Ca deficiency. At the same time, mention must be made of the prospect of a specific cation toxicity superimposed on Ca deficiency. This phenomenon may arise in an alkali soil, for

example, which might be low in Ca and high in Na. A good demonstration of this is to be found in the work of Thorne (19) in which, at a given Ca content of tomato tissue, plant growth was more restricted where Na was a complementary ion than where K was used. Yet even here the Na content of the plant tissues was much higher than the K in the respective treatments. A similar possibility may exist in the report of Joffe and Zimmerman (11), who summarized their results with several Na, Ca, and Mg ratios as indicating that a low Ca-Mg ratio behaved like a high Na content on the exchange complex.

#### SUMMARY

A soil derived from serpentine rock was tested for nutrient deficiencies on lettuce and barley grown in pots. Severe deficiencies of N and P and a slight deficiency of K were found.

The complete N, P, and K combination produced not only low yields but also disease symptoms described as a rosette in lettuce and as tip failure in barley.

The leaf symptoms were reduced and the yields increased by addition of gypsum or by leaching with  $\text{CaSO}_4$ , in conjunction with the N, P, K nutrients. No improvement was observed from leaching with  $\text{MgSO}_4$  or  $\text{K}_2\text{SO}_4$ .

Ca-Amberlite added to the soil with full nutrients produced healthy plants and excellent yields. Mg- and K-Amberlites depressed the yield and aggravated the symptoms. Sr-Amberlite gave a slight increase in yield and no appreciable change in appearance.

The lettuce rosette was produced on a highly productive soil by addition of Mg- and K-Amberlites. Ca- and Sr-Amberlites added to this soil produced healthy plants. Where the symptoms appeared, the amount of Ca in the soil had not been changed, but the degree of Ca-saturation was lower.

Where Mg was the complementary ion, there was a sharp reduction in lettuce and barley growth as the degree of Ca-saturation fell below 20 per cent. Lettuce rosette did not appear when the Ca-saturation was above 25 per cent.

Where K was the predominant complementary ion, the reduction in yield and the appearance of rosette in lettuce set in at 30 per cent Ca-saturation.

Plant-tissue analysis revealed the reduction in yield and the leaf symptoms to be a reflection of the low-Ca status of plants grown in soils at the lower degrees of Ca-saturation.

The rosette symptoms were produced on lettuce plants grown in water-culture solutions low in Ca, and more severely in solutions low in Ca and high in Mg or K. Plant-tissue analysis revealed this to be a function of the low-Ca status of the plants under the competitive influence of Mg or K.

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# DECOMPOSITION OF WHEAT STRAW BY SOME FUNGI COMMONLY FOUND IN NEBRASKA SOILS<sup>1</sup>

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Use of plant residues for control of soil and water losses has become widespread in some of the more important agricultural areas in the United States (6, 7). When residues are applied to the soil, decomposition takes place as a result of the action of various microorganisms. The rate of disappearance of residue material is greatly influenced by temperature, moisture, pH, chemical composition and state of maturity of the residue, and numbers and kinds of microorganisms present.

Since the amount of vegetation available for protecting cultivated land is limited, the rate of decomposition is of vital interest in areas where residues are employed.

The major groups of microorganisms responsible for decomposition of crop residues are the bacteria, actinomycetes, and fungi, with the protozoa and possibly the algae and other forms of organisms playing relatively minor roles. The importance of the fungi in these decomposition processes can be demonstrated easily by a casual examination of fragments of decomposing residues.

From the viewpoint of maintaining soil organic matter, the amount of carbon lost during the decomposition of plant residues is very important.

The present investigation is concerned with the decomposition of wheat straw, a highly carbonaceous plant material, by various fungi isolated from soils obtained from the vicinity of Lincoln, Nebraska. Although carried out under controlled conditions in the laboratory, these studies are based on the assumption that information obtained will eventually lead to a more effective use of crop residues in the field.

The constituents of straw most susceptible to microbial decomposition have been shown by Norman (11, 12, 13) to be cellulose and the hemicelluloses. *Aspergillus fumigatus*, *A. niger*, *A. nidulans*, *A. terreus*, and species of *Sepdeonium* and *Trichoderma* isolated from straw were capable of extensive utilization of the cellulose fraction (12). Lignin is known to be among the more resistant constituents of straw and other plant residues. It is generally agreed that decomposition of lignin takes place at a relatively slow rate. Smith and Brown (16) reported the disappearance of 60 to 90 per cent of the lignin of wheat straw

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during composting. Phillips, Weihe, and Smith (14) concluded that under proper conditions soil microorganisms could break down natural lignin, as well as pentosans and cellulose, of plant materials. Waksman (20) showed that a *Trichoderma* species was capable of utilizing the pentosan and cellulose, but not the lignin, of wheat straw.

*Aspergillus* and *Penicillium* species were found in abundance by Thaysen and Bakes (18) during the early stages of decomposition of oat straw.

*Cladosporium* species were observed by Martin (9) to constitute the predominating type of fungus present in soil containing decomposing straw.

Species of *Penicillium* and *Mucor* were found by Tyner (19) to be greatly stimulated in the rhizosphere of wheat seedlings grown in soil infested with root-rot organisms. It was pointed out that infection of the seedlings resulted in the sloughing off of dead root tissues which may furnish a suitable energy supply for the saprophytic fungi.

The decomposition of straw (4, 10, 15) and other carbonaceous residues (1) in the soil may result in the depression of available nitrogen. This phenomenon was observed by Doryland (5) as early as 1916.

#### THE "OXIDASE" REACTION

Oxidase enzymes play an important role in biological processes. In a technique described by Bavendamm (2), tannic or gallic acid agar was used for detecting the presence of oxidases produced by fungi. Bavendamm intimated that the "oxidase positive" reaction, manifested by a dark halo around the colony, was an indication of the ability of the fungus to decompose lignin. Davidson, Campbell, and Blaisdell (3), using Bavendamm's technique, found a definite parallelism between the production of "oxidases" and the ability of fungi to produce white rot of wood. Ledingham and Adams (8) noted a correlation, although somewhat questionable, between the Bavendamm "oxidase" reaction and the ability of fungi to attack lignosulfonate. In view of the available evidence indicating a relationship between the liberation of "oxidase" and fungal activity, the "oxidase" reaction of all fungi used in these investigations was determined.

#### MATERIALS AND METHODS

Ten-gram portions of mature, air-dry wheat straw, ground in a Wiley mill and passed through a 2-mm. screen, were placed in 500-ml. Erlenmeyer flasks. The air-dry material contained about 10 per cent moisture. Each flask was fitted with a two-holed rubber stopper, through which an inlet and outlet tube were inserted to permit continuous aeration and removal of carbon dioxide and ammonia. Air circulation was maintained by means of a suction pump. Inlet and outlet tubes were plugged with cotton to reduce the chances of contamination. Each flask and its contents were sterilized by autoclaving 30 minutes at 18 pounds pressure.

After sterilization, the flasks were inoculated with aqueous suspensions of 7-day cultures of recently isolated fungi grown on Sabouraud's agar slants. Plate counts were made on each inoculant to obtain an estimate of the concentration of the organisms used.

Moisture content of the plant material was then adjusted to about 300 per cent and the flasks were incubated at  $26^{\circ} \pm 2^{\circ}$  C. for 7 days. The 7-day period was chosen because the peak rate of decomposition was passed and a state approaching equilibrium usually was reached within that time.

Carbon dioxide and ammonia were removed by alkali and acid traps, respectively, from the air entering the system.

The carbon dioxide produced was absorbed in a standard solution of sodium hydroxide. Ammonia was absorbed in sulfuric acid solution and determined by Nesslerization. Fritted glass gas-dispersion tubes (Corning #39350) were placed in the absorbing solutions to ensure efficient absorption. Carbon dioxide and ammonia determinations were made at daily intervals for 5 days and again on the seventh day. The contents of the flasks were then examined for contamination by direct microscopic study and by streaking on Sabouraud's and soil-extract media. The pH and loss of weight were determined. The pH determinations were made with the Beckman glass electrode pH meter. The loss of weight was determined by weighing on the analytical balance after drying to constant weight at  $100^{\circ}$  C. before and after decomposition. In calculating weight losses allowance was made for moisture content of the original plant material. All determinations were carried out in triplicate.

The oxidase reaction of the fungi studied was determined by streaking on tannic acid agar.<sup>2</sup> With *Chaetomium*, which was acid-sensitive, it was necessary to layer the tannic acid agar with a suitable nonacid medium. The fungus was then allowed to grow, and the enzyme readily diffused into the indicator medium below.

Forty-five fungus isolates (table 1), representative of those found in soils and on decomposing plant residue and which were capable of growing on laboratory media, were used. Fifteen gave the oxidase-positive reaction, fifteen were *Aspergilli* and oxidase-negative, and the remaining fifteen were oxidase-negative and belonged to various genera other than *Aspergillus*. Various kinds of *Aspergilli*, including those producing black, tan, or green colonies, were included.

## RESULTS

### *Reproducibility of results*

A number of fungi were tested for their ability to decompose wheat straw after being carried on Sabouraud's medium for different lengths of time. Typical results of such tests with *Hormodendrum* (F-110), a fungus showing a relatively high rate of activity, and *Rhizopus* (F-108), having a very low rate of activity, are shown in figure 1. Both organisms were isolated in June 1945 and used to decompose the straw in August and again in October. These data indicate that after isolation on Sabouraud's medium, the organism is not likely to change its straw-decomposing ability for several months at least. An exception to the rule was found in a strain of *Trichoderma* which decreased considerably in its ability to decompose straw after propagation on Sabouraud's medium for several

<sup>2</sup> (a) Agar 20 gm., malt (Difco) 15 gm., water 850 ml. (b) Tannic acid (USP, powdered) 5 gm., water 150 ml. Sterilize (a) and (b) separately by autoclaving at 15 pounds for 15 minutes and add together aseptically before use.

TABLE 1

*Genus, "oxidase" reaction, and source of fungi used in the decomposition of wheat straw*

CULTURE NO.	GENUS	OXIDASE REACTION	SOURCE OF FUNGUS
F-100.....	Unknown	—	Field soil
F-101.....	<i>Aspergillus</i> (black)	—	
F-102.....	<i>Aspergillus</i> (tan)	—	
F-103.....	<i>Penicillium</i>	+	
F-104.....	<i>Alternaria</i>	+	
F-105.....	<i>Fusarium</i>	+	
F-106.....	<i>Penicillium</i>	—	
F-107.....	<i>Fusarium</i>	+	Soil incubated at room temperature
F-108.....	<i>Rhizopus</i>	—	
F-109.....	<i>Alternaria</i>	+	
F-110.....	<i>Hormodendrum</i>	+	
F-111.....	<i>Penicillium</i>	+	Decomposing straw
F-112.....	<i>Trichoderma</i>	+	
F-113.....	<i>Hormodendrum</i>	+	Field soil
F-115.....	<i>Aspergillus</i>	—	Soil incubated at room temperature
F-116.....	<i>Aspergillus</i>	—	
F-117.....	<i>Chaetomium</i>	+	
F-118.....	<i>Aspergillus</i> (black)	—	
F-119.....	<i>Aspergillus</i> (tan)	—	Field soil
F-120.....	Unknown	—	
F-121.....	<i>Aspergillus</i> (black)	—	
F-122.....	<i>Penicillium</i>	—	
F-123.....	<i>Trichoderma</i>	+	Rubber stopper
F-124.....	<i>Trichoderma</i>	—	
F-125.....	<i>Penicillium</i>	—	
F-126.....	<i>Aspergillus</i> (tan)	—	
F-127.....	<i>Aspergillus</i>	—	Greenhouse soil
F-128.....	<i>Penicillium</i>	—	
F-129.....	<i>Penicillium</i>	—	
F-130.....	<i>Aspergillus</i> (green)	—	
F-131.....	<i>Aspergillus</i> (black)	—	Decomposing cornstalks
F-132.....	<i>Penicillium</i>	—	
F-133.....	<i>Penicillium</i>	—	
F-134.....	Unknown	+	
F-142.....	<i>Hormodendrum</i>	+	Decomposing alfalfa
F-143.....	<i>Alternaria</i>	+	
F-144.....	<i>Penicillium</i>	—	
F-145.....	<i>Aspergillus</i> (black)	—	
F-146.....	<i>Aspergillus</i> (tan)	—	Air contaminant
F-147.....	<i>Penicillium</i>	+	
F-148.....	<i>Aspergillus</i> (green)	—	
F-149.....	<i>Mucor</i>	—	
F-150.....	<i>Penicillium</i>	—	Air contaminant
F-151.....	<i>Penicillium</i>	—	
F-152.....	<i>Aspergillus</i> (black)	—	

months. Passage through soil resulted in restoration of some of the lost activity.

*Decomposition of wheat straw by different fungi*

That different fungi vary greatly in their ability to attack wheat straw is shown in figure 2. *Rhizopus* (F-108) and *Penicillium* (F-106) were relatively inactive. They produced a peak rate of carbon dioxide evolution of no more than 1.5 mgm. per hour. *Fusarium* (F-107), *Hormodendrum* (F-110), and *Chaetomium* (F-117) were very active, with peak rates of carbon dioxide production ranging from 3.4 to 4.8 mgm. per hour.

According to Bavendamm's technique (2) and the terminology suggested by Davidson, Campbell, and Blaisdell (3), *Penicillium* (F-106) and *Rhizopus* (F-108) were "oxidase-negative" on tannic acid agar. The remaining three fungi were

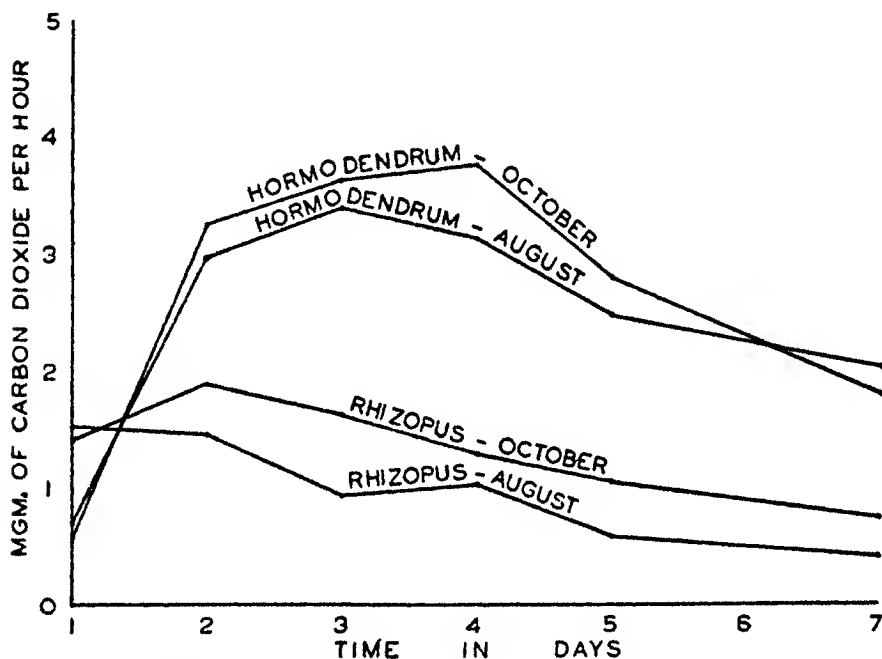


FIG. 1. DECOMPOSITION OF WHEAT STRAW BY FUNGI AT DIFFERENT TIMES

"oxidase-positive." Further observations suggested that the oxidase-positive organisms might be more active in breaking down wheat straw than the oxidase-negative ones, and that the *Aspergilli*, although oxidase-negative, occupied an intermediate position.

To test the validity of this hypothesis, 15 organisms from each of the three groups (table 1) were tested for their ability to decompose wheat straw.

The average decomposition rates for the *Aspergillus*, oxidase-positive and oxidase-negative fungi are shown in figure 3. The data were analyzed statistically and the following results obtained:

During the first day there was no difference in the average decomposition rates of wheat straw by the three groups of fungi.

During the 2nd, 3rd, 4th, 5th, and 6th plus 7th days the oxidase-positive organisms pro-

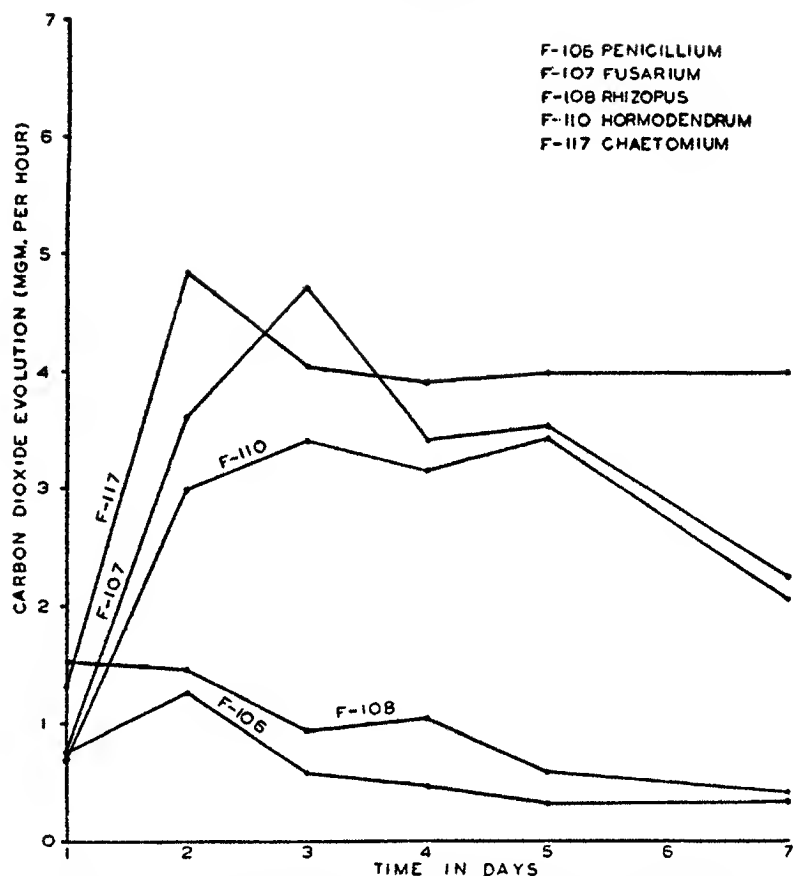
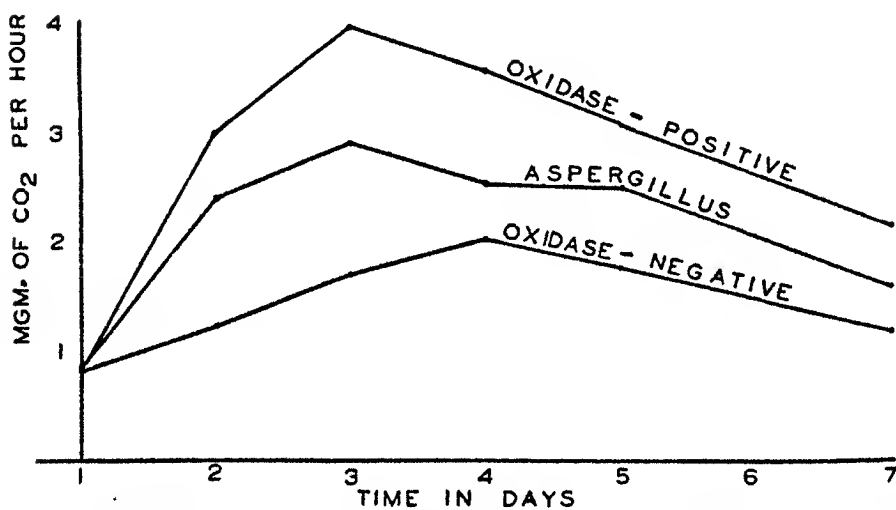


FIG. 2. RATE OF DECOMPOSITION OF WHEAT STRAW BY DIFFERENT FUNGI

FIG. 3. RATE OF DECOMPOSITION OF WHEAT STRAW BY *Aspergillus*, OXIDASE-POSITIVE, AND OXIDASE-NEGATIVE FUNGI

duced carbon dioxide at a significantly greater (1 per cent level) rate than either the oxidase-negative or the *Aspergillus* group.

During the 2nd, 3rd, and 5th days the *Aspergillus* group produced carbon dioxide at significantly greater rates (1 per cent level) than the oxidase-negative organisms. Differences between the *Aspergillus* and oxidase-negative groups were not significant on the 4th day and were significant at the 5 per cent level, but not the 1 per cent level, on the 6th and 7th days combined.

Table 2 shows the relative amount of decomposition brought about by the three groups of fungi during the first week. If we assign a value of unity to the amount of carbon dioxide produced by the oxidase-positive group, the *Aspergillus* and oxidase-negative produced 76 per cent and 53 per cent as much, respectively.

TABLE 2  
*Extent of decomposition of wheat straw by Aspergillus,  
oxidase-positive, and oxidase-negative fungi*

GROUP	GENERA INCLUDED	EXTENT OF* DECOMPOSITION	RATIO
Oxidase-positive	<i>Penicillium, Fusarium, Alternaria, Hormodendrum, Trichoderma, Chaetomium, Unknown</i>	444	1.00
<i>Aspergillus</i>	Black, tan, green, and miscellaneous <i>Aspergilli</i>	343	0.76
Oxidase-negative	<i>Penicillium, Rhizopus, Mucor, Trichoderma, Unknown</i>	234	0.53

\* Mgm. of CO<sub>2</sub> produced in 7 days from 10 gm. of straw.

#### *Ammonia losses during decomposition of wheat straw*

Ammonia was never detected in quantities in excess of a trace during the decomposition of wheat straw.

#### *Carbon dioxide evolution vs. loss in weight*

Since both carbon dioxide evolution and loss in weight are commonly employed as criteria of the decomposition of organic materials, the degree of correlation between these two values was determined. The data were obtained from wheat straw decomposed by various fungi and represent 148 observations. The results are shown graphically in figure 4 where carbon dioxide, which had been converted to its cellulose equivalent, was plotted against loss in weight.

The equations of the regression lines in figure 4 are as follows (17):

$$E = \bar{y} + \frac{S_{xy}}{S_x^2} (X - \bar{x}) = 0.29X + 80.7 \quad (1)$$

$$E = \bar{x} + \frac{S_{xy}}{S_y^2} (Y - \bar{y}) = 2.23Y - 6.3 \quad (2)$$

The linear correlation coefficient is 0.804. Since it is based on 146 degrees of freedom, it greatly exceeds the value necessary for significance at the 1 per cent

point. The relationship between carbon dioxide evolution and loss of weight is, therefore, a highly significant one. This lends support to the validity of carbon dioxide evolution as a measure of decomposition of carbonaceous residues.

In an attempt to account for loss of weight of the decomposing straw, a factor was used for converting, to its cellulose equivalent, the carbon dioxide liberated. Since straw is rich in cellulose, the assumption was made that it was the chief

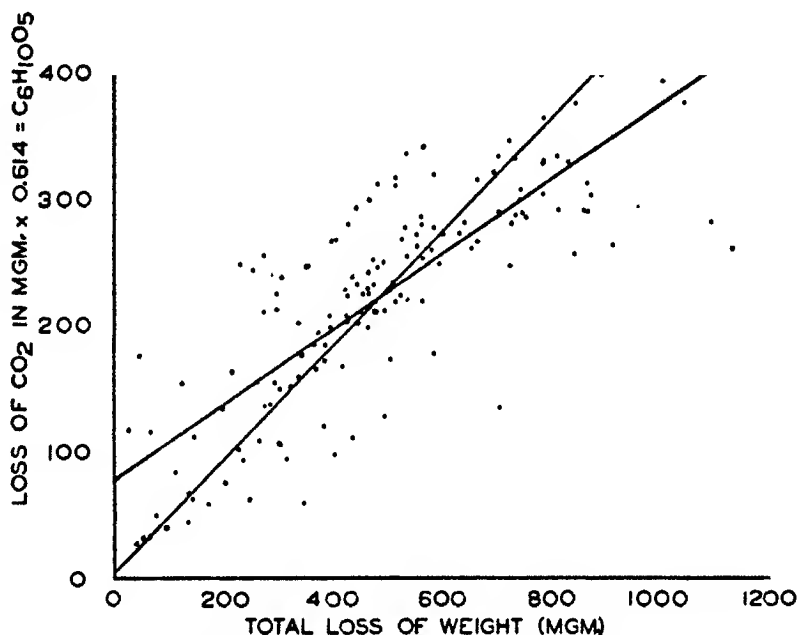
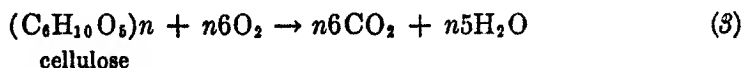


FIG. 4. RELATIONSHIP BETWEEN CELLULOSE EQUIVALENT OF CARBON DIOXIDE EVOLVED AND LOSS OF WEIGHT DURING DECOMPOSITION OF WHEAT STRAWS

constituent decomposed and that the reaction went to completion according to equation (3):



It is evident from figure 4 that the cellulose equivalent of the carbon dioxide lost does not account for the total loss in weight. The data indicate that carbon sources other than cellulose were used by the fungi, or if cellulose was the chief constituent decomposed, it was not broken down to its end-products, carbon dioxide and water.

There was no evidence of liberation of significant amounts of ammonia. It is also quite unlikely that methane, sulfur dioxide, or other reduced compounds were lost because of the aerobic nature of the process. There is a possibility that some loss of volatile constituents occurred during the oven-drying process, which was carried out at 100° C. after the carbon dioxide measurements were



terminated. Other than this, the author is unable to explain the discrepancy between carbon dioxide loss and loss in weight.

*pH changes in wheat straw during decomposition by various fungi*

Final pH values ranging from about 3 to 8.5, depending on the fungus used, resulted from the decomposition of wheat straw. Three strains of a black *Aspergillus*, probably *A. niger*, produced a distinctly acid decomposition with a pH value ranging from 3.06 to 3.36. Four strains of *Penicillium* also produced a very acid reaction (table 3). A moderately acid decomposition was produced by five strains of *Aspergillus* (table 3), which were quite different morphologically from those in the very acid group. Three of these five strains produced green colonies on Sabouraud's and rose bengal agar. The two remaining strains of *Aspergillus* in this group produced a prolific white mycelium with small blue conidial heads.

Four strains of *Aspergillus*, three of which produced tan colonies (F-102, F-119, and F-146), and one each of *Penicillium* (F-150), *Fusarium* (F-105), *Rhizopus* (F-108), *Chaetomium* (F-117), and an unidentified fungus (F-134) produced pH values close to neutral (table 3). An alkaline decomposition resulted from the action of two strains of black *Aspergillus* (F-131 and F-145), one strain of tan *Aspergillus* (F-126), six strains of *Penicillium* (F-106, F-128, F-129, F-132, F-144, and F-151), three each of *Alternaria* (F-104, F-109, and F-143), *Hormodendrum* (F-110, F-113, and F-142), and *Trichoderma* (F-112, F-123, and F-124), and one each of *Mucor* (F-149), *Fusarium* (F-107), and an unknown fungus (F-120) (table 3).

The black *Aspergilli* fell into two groups on the basis of their ability to produce pH changes during the decomposition of wheat straw. One group, comprising cultures F-101, F-121, and F-152, produced a very acid decomposition having a final pH value slightly above 3.0. The second group produced an alkaline decomposition with a final pH of approximately 8.0. The green *Aspergilli* produced a moderately acid decomposition, and the tans produced a neutral to alkaline type of decomposition.

The *Penicillia* varied widely in the type of decomposition produced. Some strains were strong acid producers, some were alkali producers, and others were intermediate between the two (table 3).

*Relationship between pH changes and amount of CO<sub>2</sub> produced*

Since acid (or alkali) production and carbon dioxide are the result of microbial activity, the question arises as to whether there is a relationship between the two. Changes in pH brought about during the decomposition of wheat straw were obtained by subtraction, after conversion to hydrogen-ion concentration, of values obtained in uninoculated controls from final hydrogen-ion concentrations of the material after decomposition. The results were then reconverted to pH. Plus values obtained in this way indicate a change in the direction of alkalinity; minus values indicate a more acid condition.

Changes in pH are plotted against CO<sub>2</sub> production in figure 5. The points

**TABLE 3**  
*Final reaction of wheat straw decomposed by different fungi*

GENUS	CULTURE NUMBER	pH
<i>Very acid (pH 3.00-4.49)</i>		
<i>Aspergillus</i> (black) .....	F-101	3.36
	F-121	3.27
	F-152	3.06
<i>Penicillium</i> .....	F-103	3.24
<i>Penicillium</i> (pigmented) .....	F-122	3.22
	F-125	3.80
<i>Penicillium</i> .....	F-147	3.58
<i>Moderately acid (pH 4.50-6.49)</i>		
<i>Aspergillus</i> (small blue heads) .....	F-115	5.99
	F-127	5.93
	F-116	6.28
<i>Aspergillus</i> (green) .....	F-130	5.84
	F-148	6.03
<i>Penicillium</i> .....	F-111	5.27
Unknown .....	F-100	5.91
<i>Near neutral (pH 6.50-7.49)</i>		
<i>Aspergillus</i> (tan) .....	F-102	6.71
	F-119	6.78
	F-146	6.58
	F-118	7.03
<i>Penicillium</i> .....	F-150	7.46
<i>Fusarium</i> .....	F-105	7.24
<i>Rhizopus</i> .....	F-108	7.41
<i>Chaetomium</i> .....	F-117	7.31
Unknown .....	F-134	7.24
<i>Alkaline (pH 7.50+)</i>		
<i>Aspergillus</i> (black) .....	F-131	7.80
	F-145	8.05
<i>Aspergillus</i> (tan) .....	F-126	8.67
	F-106	7.82
	F-128	7.87
<i>Penicillium</i> .....	F-129	8.17
	F-132	8.13
	F-144	8.12
	F-151	7.61
<i>Mucor</i> .....	F-149	7.54
<i>Alternaria</i> .....	F-104	7.56
	F-109	7.67
	F-143	8.06
<i>Fusarium</i> .....	F-107	7.78
<i>Hormodendrum</i> .....	F-110	7.91
	F-113	8.06
	F-142	8.10
<i>Trichoderma</i> .....	F-112	8.30
	F-123	8.45
	F-124	8.33
Unknown .....	F-120	7.26

are well dispersed, and there is no evidence of correlation between the two values. Some of the most active liberators of  $\text{CO}_2$  produced very little change in pH. Although the number of observations is small, the data indicate that pH measurements do not, in general, furnish reliable criteria of the amount of decomposition brought about by the fungi.

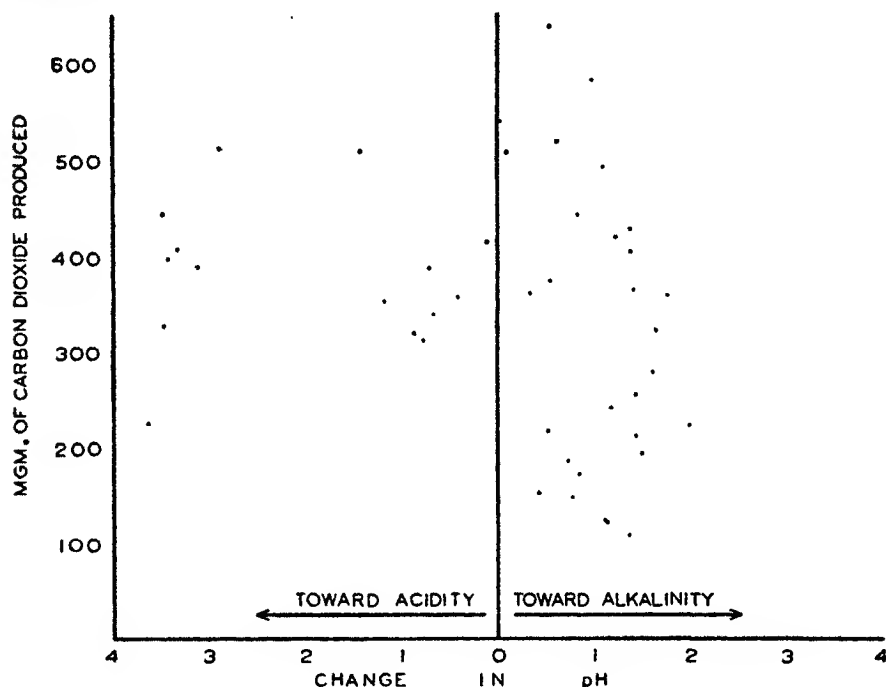


FIG. 5. RELATIONSHIP BETWEEN  $\text{CO}_2$  PRODUCTION AND RELATIVE CHANGES IN pH DURING THE DECOMPOSITION OF WHEAT STRAWS BY DIFFERENT FUNGI

The uninoculated controls are designated as 0

#### SUMMARY

The aerobic decomposition of wheat straw by a number of fungi isolated from Nebraska soils and decomposing plant materials has been studied.

Carbon dioxide and ammonia evolution, pH, and loss in weight were measured during a 7-day period of decomposition at room temperature. Carbon dioxide evolution appears to be the most reliable and convenient method of measuring decomposition or comparing the rates of decomposition brought about by different organisms.

Decomposition rates varied greatly with the kind of fungi involved. Fungi showing the "oxidase-positive" reaction on tannic acid were, as a group, more active than "oxidase-negative" fungi in decomposing wheat straw. The cultures of *Aspergillus*, all of which were oxidase-negative, were more active than other oxidase-negative fungi.

A high degree of correlation was found between carbon dioxide evolution and

loss of weight during the decomposition of wheat straw. No such relationship was found between carbon dioxide evolution and changes in pH.

Ammonia losses from wheat straw during decomposition by pure or mixed cultures were negligible.

Most of the fungi appeared to remain fairly constant in their straw-decomposing ability after isolation on artificial media. A member of the genus *Trichoderma*, however, showed wide variation in its ability to attack wheat straw, depending upon the substrate on which the organism was grown.

Values in pH ranging from very acid to distinctly alkaline were obtained in the decomposed straw. The final pH depended on the organism used.

The oxidase reaction of acid-sensitive fungi may be brought out on tannic acid agar by layering the acid medium with a suitable nonacid medium before inoculation.

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# AFRICAN CONFERENCE ON SOILS AT GOMA, BELGIAN CONGO

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On November 8, 1948, the first African Soil Conference convened under the presidency of Dr. P. Staner, Director, Belgian Ministry of Colonies, at Goma, on Lake Kivu, close to the eastern boundary of the Belgian Congo. The conference was welcomed by M. Jungers, Governor General of the Belgian Congo and of Ruanda Urundi. Present were official delegates from the Union Française, 2; French Cameroons, 2; French Equatorial Africa, 5; French West Africa, 2; Madagascar, 3; from Portugal, 1, and Angola, 1; from the United Kingdom and from British Colonies and Commonwealth: Great Britain, 2; British East Africa, 8; British West Africa, 8; Northern Rhodesia, 2; Southern Rhodesia, 3; and the Union of South Africa, 9. The Food and Agriculture Organization sent two observers. Belgium, the Belgian Congo, and Ruanda Urundi were represented by 54 delegates. The Mwami (King) of Ruanda Urundi was also present. The Institut National pour l'Étude Agronomique du Congo Belge (INÉAC)<sup>2</sup> was represented by 18, and the Institut pour la Recherche Scientifique en Afrique Central (IRSAC)<sup>3</sup> by 1.

## CROP-PRODUCTION PROBLEMS

The peculiar significance of the holding of this first African Soil Conference in the Belgian Congo will be better understood if it is briefly pointed out that there are very serious crop-production problems on lowland equatorial soils under high rainfall. As a consequence of the crusading zeal of H. H. Bennett and his school, readers in north temperate regions are well aware of the types of tragic soil erosion that continue to render worse than valueless for human use vast areas of the arid and semiarid soils of southern Africa; and the general character of the damage and the means of controlling and/or preventing it are understood. On the other

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<sup>2</sup> INÉAC, organized in 1933 to take over the scientific work in agriculture previously conducted by the Régie des Plantations, which in 1926 had taken over the scientific work and certain plantations of the official Department of Agriculture of the Belgian Congo, and by certain regional organizations, as the Comité Spécial du Katanga, is responsible for all the agricultural research in the Belgian Congo and in Ruanda Urundi. INÉAC operates as a private organization, but receives its support from the Belgian and Belgian Congo Governments. In the Belgian Congo and Ruanda Urundi, INÉAC has a staff of about 75 Belgian agricultural scientists, located at the headquarters station at Yangambi, Stanleyville Province, and at 23 widely distributed branch stations.

<sup>3</sup> Recently organized as a nonofficial agency, but supported by the Belgian Government, IRSAC will be responsible especially for encouragement of research in the natural sciences, other than agriculture, and in the social sciences. African headquarters are at Costermansville (Bukavu,) Kivu Province. (See *Science* 108: 301, Sept. 17, 1948.)

hand, travellers and others continue to write enthusiastically of the lush forest vegetation which still covers vast areas in rainy low latitude portions of the world, such as the tropical rain forest of the Congo Basin and the selva of the Amazon. To them such forest indicates soils of great potential fertility. As a consequence, even otherwise well informed agriculturists of temperate zone regions, accustomed to soils developed under moderate rainfall and lower temperature regimes, have the grossly erroneous impression that as a whole the soils carrying the luxuriant tropical forests have a high potential food- and fiber-producing capacity.<sup>4</sup>

Many have long believed that the possibilities of agricultural exploitation of the humid low latitudes would yield rich rewards. Repeated waves of agriculturists have come down to the Congo and other such equatorial regions for commercial exploitation, or as agricultural scientists, or even to make homes for themselves as settlers. Largely because of the *very low potential fertility of soils carrying high tropical forest*, and the very disappointing behavior of these soils, even under nonexploitive methods of management effective for temperate zone soils most of the attempts of all three groups have been failures. For example, here the usual herbaceous leguminous cover or green manure crops have often proved quite useless, if not deleterious, to soil fertility. After terrific financial losses and great soil damage, successful methods have been developed for rubber and other tree and shrub crops, but the continuous production by temperate zone methods of most annual field crops has seldom been successful. The natives of southeastern Asia have solved this problem by growing lowland rice, but that is another story.<sup>5</sup>

In virtually all the other regions of rainy lowland equatorial soils, the native farmer annually clears an acre or so of forest, burns the slash in this *kaingin* and, without needing to stir the soil, dibbles in the seeds of maize, upland rice, cucurbits, or other vegetable crops. Tall trees may not be cut, though perhaps they are girdled so that they will die and so make less shade for the second crop; stumps are never grubbed, rather they often sprout again, helping restore forest conditions. This is important, for the forest is really the long-term cover crop; in fact, it does more proportionately for the soil and the subsequent crops than does the cover crop in temperate zone agriculture.

Burning the slash liberates as ash the nutrients in the forest. Part of these are

<sup>4</sup> Of course, the relatively limited areas of well-drained *recent* alluvium and young soils developed from volcanic ash are actually often very fertile. Such soils are not included in the following discussion.

<sup>5</sup> When the population of the world has so increased that there will no longer be enough suitable soil and appropriate fertilizers to raise the wheat, barley, corn, and other cereals to feed the people, the proportion of lowland rice (padi) raised in the world will greatly increase. This is because almost any soil, even though it is extremely poor in the usual plant nutrients and even though its physical characteristics as judged by the usual criteria for upland crops are also poor, will produce a considerable crop of food, provided the land can be kept flooded with water a few inches deep during the preparation of the soil and the transplanting, growing, and maturing of the padi. It is thus certain that as the population of the world increases, and the fertilizer reserves decline, rice will constitute an increasing proportion of the world's food.



taken up by the growing crop; the rest are carried far away or deep into the soil by the heavy rains when the growing crop is still young. Thus, almost all the nutrients that have cycled in the living luxuriant forest are dissipated. The decline in fertility of the soil is worsened by the invasion of *Imperata cylindrica* (cogon) and other pernicious grasses.

In Northern Rhodesia, just south of the Belgian Congo, Trapnell and co-workers<sup>6</sup> have shown that an astonishing number of variations of this general type of crop production are employed by the various tribes of that colony alone. These workers have drawn attention to the relatively small number of people per square mile which these methods will support, and to the numerous modifications the natives have introduced in their attempts to get more out of the soils continually declining in fertility. As the population continues to increase, at least in part because of more peaceful conditions and because transportation and markets have made it more worth while to grow more than the family can consume, more land per family is often planted annually. Forest or brush is cut before it has regenerated the soil sufficiently, and cogon and other savanna grasses increase in quantity. Burning annually with fierce heat during the dry season, "bush fires" prevent natural regeneration of the forest. "Fire savannas" are the consequence, and they occupy vast and continually increasing areas, formerly forested, in equatorial and tropical regions. Such areas are not easily used by the natives for crop production, though the grasses do provide some poor pasture, supporting perhaps one head to each 10 acres.

In the Belgian Congo these several types of decline of fertility are included under the general term *soil degradation*.<sup>7</sup> In this colony the agricultural scientists lead the world in their recognition of the extremely limited fertility of the lowland equatorial forest soils, as well as in their extensive and intensive attempts to find rational and inexpensive solutions for this and related problems of annual crop production in low latitudes. Hence, it is peculiarly appropriate that the Belgian Congo Government should be host to the first African Soil Conference.

#### ORGANIZATION OF THE CONFERENCE

In the conference the languages used were French and English. All members of the conference are grateful to the British delegation for having brought with them Mr. Barker, a professional interpreter. During the general sessions he gave a summary in the other language of every address; he also attended all the meetings of Section 1, ably summarizing each paper in the other language, as well as the substance of the remarks of every speaker in the discussions.

A total of 181 communications were presented to the conference; 104 were dis-

<sup>6</sup> C. G. Trapnell and J. N. Clothier. The soils, vegetation and agricultural systems of North-Western Rhodesia. Government Printer, Lusaka. 1937.

C. G. Trapnell. The soils, vegetation and agriculture of North-Eastern Rhodesia. Government Printer, Lusaka. 1943.

<sup>7</sup> For a lengthy discussion of this subject, in many of its phases, as it applies to Africa as a whole but more particularly to Central Africa, see Jean-Paul Harroy, *Afrique: terre qui meurt*, pp. 548. Marcel Hayez, Imprimeur-editeur. Bruxelles. 1944.

tributed in printed form, the rest were replicated locally.<sup>8</sup> By the opening of the conference, the executive committee had classified the communications and assigned them to sections, as follows (italic numbers in parentheses indicate the number of papers):

SECTION 1—*General and regional study of soils (56)*: 8 sessions

- 1—Analysis and survey methods; general properties and classification (10).
- 2—Properties, regional classification and mapping (25)
- 3—Factors of pedogenesis; ecology and effects of the vegetation (16)
- 4—Land use (5)

SECTION 2—*Causes and signs of soil degeneration (21)*: 4 sessions

- 1—General aspects and regional situations (16)
- 2—Destruction of the vegetal cover and some causes of degradation (5)

SECTION 3—*Cultural systems in relation to soil conservation (42)*: 5 sessions

- 1—Anti-erosion technics (4)
- 2—Cultural methods (16)
- 3—Fallows and cover crops (9)
- 4—Pasture and agrostologic problems (7)
- 5—Bush and grass fires in general and their relation to animal husbandry (6)

SECTION 4—*Mechanization of agriculture and utilization of fertilizers (12)*: 2 sessions

- 1—Mechanization of agriculture (5)
- 2—Manuring, composting and fertilizers (9)

SECTION 5—*Social and economic problems in relation to soil conservation (30)*: 4 sessions

- 1—Rational organization of agriculture (15)
- 2—Population regrouping and displacing (2)
- 3—Forestry problems in relation to native economy (6)
- 4—Agricultural propaganda and education (5)
- 5—Miscellaneous (2)

Though the number of papers is no indication of relative importance, the numbers under the different sections do suggest somewhat the interests of the participants and the lines of work followed.

#### LOCALE OF CONFERENCE

This conference is notable because it is the first really representative international conference dealing with soils, soil conservation, and land use for all Africa south of the Sahara. Madagascar, having similar conditions and perhaps even more serious problems, was also included. For many agricultural scientists this conference offered the first opportunity to meet and compare notes with others who have been working for years in neighboring countries. For official employees the crossing of international boundaries while on duty is often very difficult, and colonial services frequently require that all leave be spent in a tem-

<sup>8</sup> A special issue of the "Bulletin Agricole du Congo Belge" will be issued by the Ministry of Agriculture in Brussels, containing the communications, a summary of the discussions and the resolutions adopted during the conference.

perate, northern latitude. This conference will be the beginning of personal correspondence and exchange of publications, always important, but particularly so between relatively isolated scientists. Some of us at the conference felt keenly our inability to converse freely in French; it seriously limited the range of acquaintances we could cultivate.

The conference was held almost under the Equator, at Goma, which is on the shore of Lake Kivu, 1,460 m. above sea level. Goma is also but a few miles from a center of intense and extensive volcanic activity, some within the last year. The superb scenery and the altitude result in an atmosphere hard to equal, physically and aesthetically. Because of the pre-eminence of the Belgian agricultural scientists in the Congo in dealing with the problems of lowland equatorial soils under high and more or less well distributed rainfall, it is to be regretted that more of the members of the conference could not have had at least a few days to study the experiments testing the forest/agricultural rotations and other likely methods for maintenance of soil fertility. Living accommodations for the members were, however, a limiting factor. Like many other parts of the world, the Belgian Congo is still very short of housing. This applies particularly to officials of the colonial government, who have increased greatly in numbers since the war, and who crowd the hotels of all the larger towns. Goma and neighboring Kisenyi are rather resort localities, hence under less of a housing strain during November. Even so, only the generosity of many residents in sharing their homes made it possible to accommodate the large numbers of delegates. The shortage of appropriate meeting rooms close together made it difficult to get quickly from one sectional meeting to another to hear particular papers. Local residents were very generous in doing everything possible to aid transportation, especially by using their personal cars to take the delegates to and from the meetings and from sectional meeting to sectional meeting, and to and from the numerous evening social events.

A number of good roads radiate from Goma, making possible interesting excursions. One long, two-day excursion was made through the Great Rift Valley and the Albert National Park, thence up the escarpment into the mountains to the west. Here, at the cost of considerable soil deterioration, Belgian colonists produce pyrethrum, Cinchona (quinine) bark, and dairy products—all high-value products, which will stand the cost of long road transport to markets. Of course, most delegates wanted to see the wild animals in their native environment in the Park; even some of our most able pedologists skipped the prepared profiles to see the elephants, water buffaloes, and hippopotamuses in their native haunts! On this trip one striking and unusual group of mountain soils was demonstrated in the mountains to the west of Lake Edward, at altitudes between 1,800 and 2,200 m. Below the darkening of the surface 10 to 15 cm., the profiles show gradually increasing darkening to a depth of between 1 and 2 m.; then with further depth, there is a gradual lightening of the color. It must be a peculiar temperature and rainfall regime which has caused this sort of profile to develop. The only even vaguely similar profiles I can recall having seen are in the high Andes of western Ecuador.

After the conference had closed, a smaller group of the delegates took a 4-day trip through Ruanda Urundi and the Kivu, particularly to see the diverse activities of the Anti-Erosion Service. In contrast with some other parts of the Belgian Congo where considerable mapping of soils and analyses of samples has been done, the study of the soils in the Kivu has only recently begun. The emphasis in this province is now upon the semiarid Ruzizi Valley, between Lakes Kivu and Tanganyika, with its possibilities of increasing cotton production and of settling some of the excessively dense rural population from Ruanda Urundi, just to the east.

Plainly visible on these trips were the results of much activity on the part of extension officers in encouraging the making of hedges on the contour, to develop terraces and to facilitate strip cropping. Despite the steepness of the slopes of much of the land, and the recent adoption of the soil conservation measures, however, soil erosion and the need for soil conservation practices seem to be of surprisingly little importance as yet in this part of Africa. Nevertheless, as is usually the case, the field trips offered an effective way to become better acquainted with other pedologists and so served their main purpose.

#### RESOLUTIONS OF THE CONFERENCE

The final general session of the conference was held on November 16. At this session were presented the resolutions which epitomized more or less successfully the more important points of view presented in papers and developed in the discussions. The most significant resolutions provided for setting up regional committees of soil scientists in the principal regions of Africa and for developing a central pedological service under INÉAC, at Yangambi. Encouragement of travel for soil scientists between the various countries and colonies is much to be desired; more frequent intercourse will contribute materially to a better understanding of the soils, and the methods for the solution of the very difficult soil fertility conservation, soil erosion control, and land-use problems which in various aspects face all countries of Africa. Another resolution provided for establishment of an inter-African bureau of soil erosion and soil conservation with headquarters in Paris. Finally, it was decided that a second African soil conference should be held in 1953.

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